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PRESSURE TUBE RUPTURE IN A CLOSED TANK: FEASIBILITY STUDY

By

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PRESSURE TUBE RUPTURE IN A CLOSED TANK: PHASE I - FEASIBILITY STUDY

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ABSTRACT

A study has been prepared on the feasibility of conducting pressure tube/calandria tube rupture tests in a closed tank, simulating a scaled-down calandria vessel. The study includes: i) a review of previous work, ii) an analytical investigation of the scaling problem of the calandria vessel and relevant in-core structures, iii) selection of a method for initiating pressure tube/calandria tube rupture, iv) a set of specifications for the test assembly, v) general arrangement drawings, vi) a proposal for a test matrix, vii) a survey and evaluation of existing facilities which could provide the required high pressure, temperature and fluid inventory, and viii) a cost estimate for the detailed design and construction, instrumentation, data acquisition and reduction, testing and reporting. The study concludes that it is both technically and practically feasible to conduct pressure tube rupture tests in a closed tank.

RÉSUMÉ

Une étude a été préparée afin de déterminer la possibilité de faire des essais de rupture de tubes de force et de tubes de guidage dans un réservoir fermé simulant une cuve réduite à l'échelle. L'étude comprend: i) une revue du travail accompli au préalable, ii) des recherches analytiques du problème d'échelle de la cuve et des structures à l'intérieur de la cuve, iii) le choix d'une méthode pour déclencher la rupture des tubes de force et des tubes de guidage, iv) un ensemble de spécifications pour la montage de l'essai de rupture, v) des dessins de la disposition générale, vi) un projet de matrice pour l'essai, vii) un examen et évaluation des installations actuelles susceptibles de produire les conditions de pression, de température et de quantité du fluide appropriées; et viii) un calcul estimatif des coûts pour la conception détaillée, la construction, l'instrumentation, l'acquisition et la réduction de données, l'essai et le rapport. L'étude conclut que les essais de rupture de tubes de force dans un réservoir fermé sont réalisables tant du point de vue technique que pratique.

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NOMENCLATURE

A	Area, (m^2)
B	Constant in Equation (4.1), (MPa)
C_m	Speed of sound in water, (m/s)
C_p	Specific heat, (kj/kg K)
d	Diameter, (m)
e	Specific internal energy, (kj/kg)
E	Modulus of elasticity, (Pa)
$\bar{E}$	Total internal energy, (kj)
f	Friction factor, dimensionless
F	Flexibility, (m^5/N)
g	Gravitational acceleration, (m/s^2)
h	Enthalpy, (kj/kg)
h_c	Condensation heat transfer coefficient, (kW/m^2 K)
h_{fg}	Latent heat of vapourization, (kj/kg)
I	Second moment of Area, (m^4)
K	Spring stiffness, (N/m)
K_1	Damping coefficient, Ns/m^4
K_2	Damping coefficient, Ns^2/m^5
$\bar{K}$	Loss coefficient, dimensionless
L	Length, (m)
m	Mass per unit length, (kg/m)
$\dot{m}$	Mass flow rate, (kg/s)
M	Mass, (kg)
Ma	Shock Mach number, dimensionless

n	Exponent in Equation (4.1), dimensionless
N	Number of relief pipes, dimensionless
p	Pressure, (kPa)
Q	Heat rate, (kW)
r	Radius, (m)
t	Time, (s)
T	Temperature, (K)
u	Moderator fluid velocity, (m/s)
v	Moderator column velocity, (m/s)
V	Volume, (m^3)
x	Axial location, (m)
y	Deflection, (m)

Greek Symbols

α	Source strength, (m^3/s)
β	Number defined in Equation (4.32), (m^{-1})
Δt	Wall thickness, (m)
γ	Ratio of specific heats, dimensionless
ω	Natural frequency, (rad/s)
ρ	Density, (kg/m^3)

Subscripts

avg	Average
b	Bubble
c	Condensate
cool	Moderator cooling water
disc	Rupture disc
e	Exit
g	Cover gas
i	Inlet or inner
md	Moderator
ms	Mild steel
o	Initial or reference
PT	Pressure tube
r	Relief pipe
s	Spring
sc	Scaled shut-off-rod guide tube
shock	Shock front
sv	Scaled vessel
SORGT	Typical CANDU shut-off-rod guide tube
v	Vessel
ZrNb	Zirconium-2.5% wt Niobium
1	First mode

1. INTRODUCTION

1.1 Overview

The consequences of pressure tube rupture on in-core components have been examined in a Technology Review [1], with the objective of identifying and evaluating "...the phenomena (resulting from pressure tube failure) which can be shown by empirical reasoning to be capable of causing failure of other parts of the reactor." One of the recommendations of this study is that pressure tube/calandria tube rupture tests be conducted in a scale model of a calandria vessel to determine the resulting loadings and extent of damage to different in-core structures. The calandria vessel is to be scaled down in diameter only and must correctly model the structural response of the corresponding full scale calandria vessel.

Westinghouse Canada Inc. has been awarded a contract by the Atomic Energy Control Board (AECB) to study the feasibility of conducting pressure tube/calandria tube rupture tests as recommended in Reference [1]. The objectives of the study, as indicated in the AECB's 'Statement of Work' (see Appendix A), include: i) recommendation of a calandria vessel scaling scheme and special design features which would not hinder representative thermohydraulic phenomena and structural response to occur, ii) defining a procedure to initiate the pressure tube/calandria tube rupture, iii) defining the required instrumentation coverage to fully characterize the thermohydraulic phenomena and the structural response, iv) proposing a test matrix with a progressive test plan which would avoid damaging the tube array prematurely, v) survey and evaluation of existing facilities which could provide the required high pressure, temperature and fluid inventory, and support staff, and vi) providing a detailed cost estimate for the design and construction, instrumentation, data acquisition and reduction, conducting the test program and reporting.

1.2 CANDU Reactors

A CANDU reactor [2,3] is a pressure tube reactor cooled and moderated by heavy water. Figure 1 shows a typical CANDU reactor assembly. The reactor consists of a cylindrical stainless steel calandria vessel which contains the heavy water moderator, reactivity control mechanisms and fuel channel assemblies arranged in a square lattice. Each fuel channel assembly consists of a zirconium-2.5% wt.niobium pressure tube enclosed by a Zircaloy-2 calandria tube. The gap between the pressure tube and the calandria tube is filled with nitrogen or carbon dioxide at 0.1 MPa to provide thermal insulation. Inside the pressure tube there are 12 fuel bundles of the 37 element-type (see Figure 2) and the heavy water coolant. Each pressure tube is rolled into the grooved hub of a stainless steel end fitting as shown in Figure 3. A 50 mm side port near the outboard end of each end fitting is connected to the inlet and outlet feeders. A flexible seal disc mounted on a body which has a set of extendable jaws locks firmly into each end fitting to provide channel closure. A shield plug is locked into each end fitting.

The reactivity is controlled by both solid and liquid neutron absorbing systems. Fast reactor shut down is achieved by inserting a number of vertical shut-off- rods through their guide tubes, or by injecting liquid neutron-poison into the moderator through several horizontal injection nozzles. Figure 4 shows a typical CANDU channel lattice geometry, and the relative size and location of a shut-off-rod guide tube.

The moderator bulk temperature is maintained constant at approximately 72°C by continuously circulating the moderator through an external water-cooled heat exchanger. The moderator fluid is admitted to the calandria vessel through a set of nozzles, and is drawn from the calandria vessel through the exit nozzles located at the bottom of the calandria vessel. Four relief pipes, each having a rupture disc, are connected to the top of the calandria vessel as shown in Figure 1. The pressure rating of the rupture discs is 137.8 kPa gauge [1] (20 psig). Under normal operating conditions a small moderator column occupies part of the relief pipes, and helium at a slight pressure is used as cover gas.

1.3 Outline of the Remaining Chapters

The remainder of this report contains the details of the feasibility study. Chapter 2 presents a summary of the findings and recommendations of the technology review [1]. The prerequisite test facility specifications are listed in Chapter 3. The scaling problem and possible scaling schemes for the calandria vessel and the relevant in-core components are discussed in Chapter 4. Chapter 5 defines the method of initiating the pressure tube/calandria tube rupture. The test facility is discussed in Chapter 6. Chapter 7 is a list of the specifications of the test facility major components. Chapter 8 lists the instrumentation required to conduct the proposed test program. The requirements of the data acquisition system are outlined in Chapter 9. The experimental aspects of the test program including a proposed test matrix are addressed in Chapter 10. Chapter 11 contains the findings of a nation-wide laboratory survey, and a detailed cost estimate and schedule for the design and construction of the test facility, and for conducting the proposed test program. The conclusions of the feasibility study are outlined in Chapter 12.

2. SUMMARY OF THE TECHNOLOGY REVIEW [1]*

2.1 Overview

To provide brief background information, a summary of the findings of the Technology Review [1] is presented below. The study reviewed the possible set of direct consequences of failure of a pressure tube in a typical CANDU reactor with the goal of identifying and evaluating the phenomena which can be shown by empirical reasoning to be capable of causing failure of other in-core components of the reactor. The report also analyzed tube burst phenomena. Results from relevant experimental and analytical studies were presented and conclusions drawn.

In the following we present the possible failure mechanisms identified in Reference [1], the main conclusions from both experimental and analytical studies, and the main recommendations for further studies*.

2.2 Possible Failure Mechanisms

The potential damage to the following components was considered:

(1) Other pressure tubes (propagating failure).

(2) Shut-off-rod guide tubes.

(3) Poison injection nozzles.

(4) The calandria vessel.

Both short-term and long-term failure mechanisms were addressed, these are:

2.2.1 Short-term Mechaniams

These mechanisms result from the short-term forces (tens of milliseconds) due to a possible shock wave (sudden expansion of high pressure coolant into the moderator), and pressure wave due to the addition of the coolant volume into the calandria vessel. The following short-term failure mechanisms were identified:

(1) impulsive loading on adjacent calandria and pressure tubes, and shut-off-rod guide tubes,

(2) deflection of adjacent structures, and

(3) impulsive loading on the calandria vessel.

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* All the statements and conclusions listed in this chapter are summaries of those reached by the authors of Reference [1]. Also, all references other than Reference [1] are references cited in Reference [1].

2.2.2 Long-term Mechanisms

Four long term mechanisms were identified, these are:

(1) collapse of large vapour pockets leading to large hydrodynamic forces applied to neighbouring structures,

(2) missile damage caused by the ejection of fuel bundles or fragments from the ruptured pressure tube,

(3) sustained jet impingement resulting from the flashing fluid issuing from the break, and

(4) pipe whip from the ruptured pressure tube.

2.3 Conclusions From Experimental Work [1]

Results from tests in both open and closed vessels were presented. The main conclusions with regards to possible damage to in-core structures are listed in Sections 2.3.1 through 2.3.4 below.

2.3.1 Possibility of Propagating Pressure Tube Failure

(1) Tests on pressure tubes bursting in pools have failed to supply evidence of propagating tube failure (except in one case [4] where supercritical water was used).

(2) There is abundant evidence of collapse of calandria tubes on their pressure tubes.

(3) Vapour collapse, followed by damaging pressure pulses, appears not to be a serious threat in a calandria vessel with essentially no gas cap. However, experimental evidence is largely missing.

(4) The possible initial shock wave (considered weak) has not been detected.

(5) Missile damage is not conclusively settled. Evidence of damage exists, but not enough to cause propagating pressure tube failures.

(6) No damage was detected due to coolant jet.

(7) Length and orientation of the defect affect the loading on adjacent pressure tubes.

(8) Damage due to pipe whip was not found.

In summary, no mechanisms were identified which were able to produce large enough forces to cause rupture of a second pressure tube.

2.3.2 Possible Damage to Shut-off-rod Guide Tubes (SORGTs) and Poison Injection System

(1) There is no doubt that pressure impulses following pressure tube burst can crush SORGTs near the burst location. The question is how many will be damaged?

(2) Missile damage and collapse of SORGTs were demonstrated in one test [5].

(3) Very little work has been done on the loading of SORGTs from hot-water-filled pressure tube bursting in pools or vessels.

(4) The SORGTs appear to be vulnerable to crushing under the impulse imparted by the initial shock wave, jet discharge, pressure pulse loading and pipe whip.

(5) Test data are unavailable on the strength of the poison injection pipes. Two or more have to be crushed at the entrance before serious interference with the system takes place.

2.3.3 Possible Damage to Calandria Vessel

(1) Pressure impulses imparted to the calandria vessel are likely to cause tensile stresses well within the elastic limit, even when tube burst occurs near the vessel wall. This conclusion assumes only one pressure tube would be ruptured.

(2) If propagating pressure tube failure is a realistic possibility, and if the propagation happens before rupture discs open, then plastic deformation or damage to the calandria vessel may be possible.

2.3.4 Questions Unanswered by Experiments to Date

(1) Effect of irradiation of Zircaloy-2 to reactor levels on the vulnerability of the tubes under impulse loading.

(2) The magnitude of impulse due to collapse of vapour zone in a horizontal axis calandria vessel with essentially no gas cap (expected to be small).

(3) The magnitude of the impulses which may be imparted to SORGTs, and the number which may be damaged.

(4) Speed of propagation of a crack in an embrittled Zircaloy tube and the magnitude of the resulting loading.

(5) The hydrodynamics in the Isles [4] test tank which caused rupture of another pressure tube, far removed from the burst pressure tube.

2.4 Conclusions From Analytical Models [1]

The consequences of the rupture of one pressure tube were assessed by Henry [6] using what he termed "a conservative approach". He concluded that:

(1) An adjacent pressure tube will deflect elastically, and suffer no permanent damage.

(2) An adjacent calandria tube will impact on the pressure tube it encloses.

(3) The calandria vessel maximum combined stress is well within the elastic limit.

(4) The number of SORGTs disabled by the initial hydrodynamic transient and long term damage mechanisms is between two and four depending on the nature and location of the break.

(5) Possible damage to SORGTs is confined within 0.5 m from the break location.

2.5 Conclusions From Computer Simulations [1]

Using the PISCES [7] computer code to simulate the postulated pressure tube rupture, the following conclusions were obtained.

(1) Fluid-structure interaction is important.

(2) Shock wave strength depends on initial coolant pressure, whereas bulk pressurization depends on initial coolant temperature.

(3) Impulse on the calandria vessel is mainly caused by bulk pressurization.

(4) Maximum membrane stress on the calandria vessel in both peripheral and central rupture is well within the elastic limit.

(5) The forces on adjacent tubes are mainly due to the pressure differences across the tubes. Velocity of impacting fluid has little contribution.

(6) Henry's model and computer simulation predicted comparable loads on an adjacent pressure tube assuming an axial pressure tube split of 3 m. These calculations agree with the Bettula II test results [8] and are conservative.

2.6 Conclusions on Modes of Bursting [1]

(1) Spontaneous propagation of cracks in unweakened tubes is not subject to exact simulation since experimental data are not available.

(2) Generally, long axial flaws or breaks are more dangerous than circumferential ones.

(3) Circumferential breaks could conceivably be more dangerous in terms of missile damage. However, experimental tests do not substantiate this argument. Thus, axial split is considered the most serious.

(4) The medium surrounding the tube, the coolant inside it and its temperature are important in studying crack propagation.

(5) Further understanding of the tube bursting process requires detailed visual study with full scale zirconium-2.5%Nb tubing with realistic coolant and moderator conditions.

2.7 Recommended Further Experimental Investigations [1]

2.7.1 Explosion Chamber

(1) Length of vessel should be equal to length of calandria vessel.

(2) Full size diameter is desirable, but if a smaller diameter is used then energy absorbent material is to line the vessel internally to reduce loadings and reflections of shock waves and pressure wave.

(3) Special windows to be installed, for high speed photography.

2.7.2 Explosion Tube

(1) Full size pressure tube with insulation on the outside to prevent boiling of the surrounding moderator.

(2) The machined defect could be an axially milled slit.

(3) For crack propagation studies, the machined section of the pipe could be enclosed within a glass tube. Nitrogen gas is to be circulated in the annulus to prevent condensation.

(4) Pressure transducers inside the tube are needed to measure the pressure at the crack tip.

(5) Dummy fuel bundles are to be used in some tests.

(6) Electrical heating to produce axial temperature gradients should be used in some tests.

2.7.3 Pressure Tube and SORGT at Target

(1) Pressure transducers are to be placed axially to measure both the dynamic and static pressures.

(2) Strain gauges are to be mounted on the target tube to record deformation history.

(3) Pressure transducers are to be mounted inside the vessel orthogonal to the burst tube to measure spatial pressure distribution.

(4) Same instrumentation to be mounted on SORGTs when they are targets.

2.8 Recommended Further Analytical Studies [1]

(1) Three-dimensional simulation of the phenomena associated with the pressure tube rupture is desirable. One code which is capable of 3-D simulation is the PISCES [7] code, however, thermal non-equilibrium effects should be incorporated.

(2) Accurate modelling of axial split of the explosion tube is desirable. Conceptual modelling methods were briefly discussed.

(3) In order to minimize the analytical investigation cost, it would be more cost efficient for the investigator to acquire the skills to run the computer simulation code.

3. PREREQUISITE TEST FACILITY SPECIFICATIONS

For the purpose of the feasibility study, based on other considerations (see References [9] and [10]), some essential test facility features were specified as prerequisites. These features are listed below.

3.1 Channel Array

The scaled vessel is required to have provision for a square array (5 x 5 array with no corner channels) of up to 21 full size pressure tube/calandria tube (PT/CT) assemblies, all having real Zircaloy-2 calandria tubes. This assembly includes one burst PT/CT assembly, up to two target PT/CT, and up to 18 dummy PT/CT assemblies. The target channels are those directly facing the burst pressure tube defect, and 180° behind the defect. The dummy channels would have simulated mild steel pressure tubes, and simulated fuel of representative weight. The design of the scaled vessel and channel/vessel assembly must allow for the relocation of any channel in any of the 21 channel penetrations, and for post-test inspection of all in-core structures.

The target channels are required to be pressurized with hot water at the burst channel operating conditions, but with minimal circulation. On the other hand, the dummy channels are not required to be heated or pressurized, and they are open from both ends.

3.2 Discharge Water Inventory System

The supply vessel(s) should have sufficient hot light water inventory for discharge through the rupture for up to two minutes, this requirement would allow characterizing delayed thermohydraulic phenomena and structural response until the shut-off-rods are inserted through their guide tubes. Two specific options for the discharge duration are required: (i) a short duration option of 60 s, and (ii) a long duration option of 120 s. In both of these cases the maximum expected rupture flow rate is 200 kg/s.

During discharge, a specific pressure-time history in the supply vessel (simulating the expected header transient) is required to be followed. Figure 5 shows a reference example for such a history. However, provision must be made for other pressure-time histories as well, specifically, for a higher initial pressure (11 MPa) decreasing with time at the given slope for the reference example, or at a steeper slope.

3.3 Reactivity Control Mechanisms

The test facility is required to have 11 simulated shut-off-rod guide tubes, and one simulated adjuster rod assembly.

3.4 High Speed Photography

The design of the scaled calandria vessel must provide special windows to be used for recording the post rupture behaviour, using high speed video cameras.

4. THE SCALING PROBLEM

As indicated in Section 1.1, one of the objectives of the present study is to recommend a scaling scheme for the calandria vessel and the relevant in-core components. The calandria vessel must be able to house up to 21 full-size PT/CT assemblies arranged in a square lattice, 11 scaled SORGTs, and one scaled adjuster rod assembly as mentioned in Section 3.1. The calandria vessel scaling scheme, design features and fluid conditions must allow the generation of all representative pressure and temperature transients, the characterization in full detail of the thermohydraulic phenomena and associated structural loadings, and the inspection of all in-core components following each test. Since the shut-off-rod guide tubes are shorter than those in a typical CANDU reactor a scaling scheme is required to simulate the dynamic response of the SORGTs. Also, dummy channels require simulated pressure tubes, and representative weights to simulate the channel mass.

In this chapter, the scaling schemes for the calandria vessel, the shut-off-rod guide tubes and the dummy fuel channels are discussed in detail.

4.1 The Calandria Vessel

The thermohydraulic phenomena associated with pressure tube/calandria tube rupture in the calandria vessel are complex. However, two distinct terms can be defined:

(a) short term phenomena (tens of milliseconds), and

(b) long term phenomena (tens of seconds)

The phenomena associated with the short term period are shock waves due to the sudden expansion of the coolant into the moderator, and transient bulk pressurization due to the continuous addition of coolant volume into the moderator. During this period, the moderator pressure will oscillate with decreasing amplitude, and the moderator will be forced through the relief pipes until the rupture discs open [12].

At the end of the short term period a pressure plateau is reached [11] and a long term period (up to 60 s) starts until reactor shut-down, through insertion of the shut-off-rods or liquid poison injection, takes place. During this period the moderator bulk temperature will rise.

4.1.1 Literature Survey

In order to scale the calandria vessel, proper simulation of the above phenomena must be made. A literature search was carried out to survey various aspects of scaling, from basic theoretical considerations to practical approaches.

The design of a scale model requires that all important phenomena be preserved. Small scale modelling laws, based on geometrically scaled* models can be derived by either (a) non-dimensionalizing all the governing equations, their boundary conditions, their initial conditions and state properties or (b) using dimensional analysis [13], starting from the knowledge of the physical quantities which uniquely specify the problem.

Based on the first approach, a generalized method of similitude [14] provides model laws from a complete problem formulation, and gives the starting point for scale-modelling thermohydraulic phenomena. A systematic approach was formulated by Moody [15] for the design of scale model experiments to study heat, thermodynamic, and fluid phenomena in nuclear containments. Model laws were summarized for several cases which include suppression pool motion, pipe rupture discharge, vessel blowdown, containment pressurization, submerged jet action, and convective motion. The procedure was formulated both to display requirements for scale model design, and to help determine which effects cannot be scaled in a given system.

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* A geometrically scaled model is a model of a prototype where the ratio between any dimension in the model and the corresponding prototype dimension is constant. This constant is known as the scale factor (< 1.0).

The second approach was used by many workers. The approach is simpler in application than the first one, however, it does not show which effects can be neglected. Using dimensional analysis, Sonin et al [16] studied the scaling laws governing the displacement of air, contained in the drywell of a BWR, in the vents and its injection into the water of the wetwell (suppression chamber) during a hypothetical loss of coolant accident (LOCA). Sonin [17] also used dimensional analysis to derive scaling laws for small-scale modelling of steam relief into water pools. The method of Sonin [16] was later improved [18] to include evaluation of load oscillations due to fluid structure interaction. The principles of dimensional analysis were also used in scale modelling in liquid metal fast breeder reactor (LMFBR) safety analysis [19] to study the loads and structural responses of reactor vessels to hypothetical core disruptive accidents (HCDA).

The above scaling approaches depend on the classical theory of scaling which starts by geometrically scaling the components of interest, and then applying the theory of similitude. Such an approach cannot be applied for the purpose of this study, since some of the components are full scale, e.g., the fuel channels and the length of the calandria vessel. Thus, we have chosen to model each individual phenomenon and, through a parametric study, determine the important parameters for scaling purposes.

4.1.2 Short-term Phenomena

4.1.2.1 Shock Waves

The sudden release of the primary coolant into the moderator can be modelled as shock tube phenomenon [11]. Suppose that the primary coolant is initially at a pressure p_{PT}, and the moderator is initially at a pressure p_{md}. The equation of state, as shown by Cole [20], for light water can be expressed as

$$(p + B)\,\rho^{-n} = \text{constant} \tag{4.1}$$

where p is the pressure, ρ is the water density and B and n are constants.

For the purpose of this study, the values of the constants B and n for light water will be used, specifically 295.9 MPa and 7.4, respectively.

Considering the relative dimensions of the calandria and the initial wave front it is reasonable to assume that a spherical shock wave is generated [11]. If the initial shock front pressure is P_{shock}, the initial shock strength p_{shock}/p_{md} can be obtained from [11,21].

$$\frac{p_{md}+B}{p_{PT}+B} = \left(\frac{p_{md}+B}{p_{shock}+B}\right)\left\{1 - \frac{n-1}{2n}\,\frac{\dfrac{p_{shock}+B}{p_{md}+B} - 1}{1 + \dfrac{n+1}{2n}\left(\dfrac{p_{shock}+B}{p_{md}+B} - 1\right)}\right\}^{\frac{2n}{n-1}} \tag{4.2}$$

For assumed reactor operating conditions p_{md} = 0.14 MPa and p_{PT} = 10 MPa, and light water constants, Equation (4.2) yields

$$p_{shock} = 5.01 \text{ MPa}$$

It can be shown [1] that for the given values of p_{md} and p_{PT}, the particle velocity is small. In fact, the shock Mach number Ma is nearly unity (Ma = 1.009).

Kumar [11] has studied the shock wave problem in detail, with the following conclusions being reached regarding the shock front propagation:

(a) peak pressure at the shock attenuates as 1/r, and

(b) the pressure behind the shock front decays approximately as $t^{-2/3}$,

where r is the shock front radius and t is time.

The first conclusion is of particular importance in the scaling of the calandria vessel. Assuming a central pressure tube rupture, and since the pressure tube radius is 0.0515 m and the calandria vessel radius is approximately 3.8 m, the peak pressure at the shock will attenuate to the moderator pressure at a radius of 1.84 m.

The above result indicates that, if the generated shock wave has any damaging potential to the in-core components, it has to be due to the first shock.

From the vessel scaling point of view, one can reduce the vessel diameter down to 3.68 m (1.84 x 2), i.e., the diameter at which the possible centrally generated shock wave attenuates to the moderator pressure. However, if a peripheral tube rupture is to be studied, it is desirable to maintain the distance between the closest pressure tube in the test array and the scaled vessel wall prototypical, which is approximately 0.8 m in a typical CANDU reactor. If this distance is maintained, the scaled vessel diameter would be 3.11 m.

In order to have a reasonable compromise between the two possible diameter choices, and also from the consideration of long term bulk temperature rise (to be discussed later in Section 4.1.3), it is recommended that the inside diameter of the vessel be 3.35 m. This means that the distance between the closest channel, in the test channel array, and the scaled calandria vessel wall is 0.92 m. The maximum expected shock front pressure at the scaled calandria vessel surface from a central tube rupture would be 0.155 MPa. Thus, the possible wall reflected shocks would be weak and, for all practical purposes, their effects can be ignored.

4.1.2.2 Transient Bulk Pressurization

Following the rupture of a pressure tube/calandria tube assembly, the coolant will continuously flash into the moderator. As a result, the calandria pressure will rise and eventually force the moderator through the relief pipes. Because of the flexibility of the calandria vessel, its volume changes with the pressure change. In addition, all in-core flexible components, e.g. the moderator fluid and the calandria tubes, experience volume changes due to the change in pressure. A theoretical formulation presented by Pendergast [22] was modified and applied to study the bulk pressurization phenomena. The modifications included taking into account the effects of

(a) flashing primary coolant,

(b) bubble condensation, and

(c) relief pipe cover gas compression.

The model is described below.

4.1.2.2.1 Model Description

Figure 6 shows a schematic of the system under consideration. The calandria vessel is approximated by a spherical shell having the same moderator volume as the reactor calandria, and the same flexibility F_v (where the flexibility is defined as the rate of change of vessel volume with respect to the change in pressure). Only the ruptured pressure tube is considered from the array of channels and is treated as a source term located at the centre of the vessel. There are N relief pipes, connected to the top of the vessel. Each pipe has a rupture disc at the discharge end. The moderator column, and cover gas type and initial pressure are prototypical.

(a) Assumptions

The following assumptions are made.

(1) Spherical symmetry prevails.

(2) The flashing primary coolant forms an expanding central bubble which is surrounded by an incompressible liquid.

(3) Disturbance of the fluid due to the flow field at the relief pipe is neglected.

(4) The kinetic energy of the shell is neglected.

(5) The relief pipe rupture discs open instantaneously when the cover gas pressure reaches the rupture disc rating.

(6) The effect of calandria tubes flexibility and/or collapse are neglected.

(b) The Governing Equations

The equations of continuity and conservation of radial momentum for the incompressible fluid are given by

$$\frac{\partial}{\partial r} [\, u\, r^2] = 0 \tag{4.3}$$

and

$$-\frac{1}{\rho_{md}} \frac{\partial p}{\partial r} = \frac{\partial u}{\partial t} + u \frac{\partial u}{\partial r} \tag{4.4}$$

Where u and p are the fluid velocity and pressure, respectively, at any radial position r. The fluid density is ρ_{md} and the time scale is t.

Integrating Equation (4.3) yields

$$u\, r^2 = \alpha(t) \tag{4.5}$$

where α is a time-dependent parameter.

Substituting Equation (4.5) into Equation (4.4) yields

$$-\frac{1}{\rho_{md}} \frac{\partial p}{\partial r} = \frac{\frac{d\alpha}{dt}}{r^2} - 2\frac{\alpha^2}{r^5} \tag{4.6}$$

As discussed in Reference [22] it is appropriate to introduce damping terms into Equation (4.6). The author [22] postulates that the radial pressure gradient in the fluid will depend on damping terms which vary directly as the velocity and as the square of the velocity. The coefficients associated with these terms are denoted by K_1 and K_2 respectively. Upon the addition of these terms, Equation (4.6) can be integrated from the bubble radius r_b to the vessel radius r_v to yield

$$\frac{d\alpha}{dt} = \frac{1}{\frac{1}{r_b} - \frac{1}{r_v}} \left\{ \frac{p_b - p_{md}}{\rho_{md}} - \frac{\alpha^2}{2} \left(\frac{1}{r_b^4} - \frac{1}{r_v^4} \right) \right.$$

$$\left. - K_1 \frac{\alpha}{\rho_{md}} \left(\frac{1}{r_b} - \frac{1}{r_v} \right) - K_2 \frac{\alpha^2}{3\rho_{md}} \left(\frac{1}{r_b^3} - \frac{1}{r_v^3} \right) \right\} \tag{4.7}$$

where p_b is the pressure inside the expanding bubble and p_{md} is the moderator pressure at the vessel wall.

At the bubble surface condensation is assumed to take place. If we further assume that the condensation process is uniform, the liquid velocity at the bubble surface would be given by [23]

$$u_{r=r_b} = \frac{dr_b}{dt} + u_c \tag{4.8}$$

where u_c is the velocity at which the condensate leaves the bubble surface.

Substituting Equation (4.5) into Equation (4.8) yields

$$\frac{dr_b}{dt} = \frac{\alpha}{r_b 2} - u_c \tag{4.9}$$

The condensation process is simply treated by the standard convective relationship [1]

$$Q = h_c A_b (T_b - T_{md})$$

where h_c is an appropriate condensation heat transfer coefficient, A_b is the bubble surface area, T_b is the bubble temperature and T_{md} is the bulk moderator temperature.

A heat balance at the bubble surface results in the following equation for the rate of condensation $\dot{m}_c$

$$\dot{m}_c h_{fg} = h_c A_b (T_b - T_{md}) \tag{4.10}$$

Equation (4.10) can be used to determine the condensate velocity u_c

$$u_c = \frac{h_c}{h_{fg}\rho_c} (T_b - T_{md}) \tag{4.11}$$

The equations of conservation of mass and energy for the bubble are given by

$$\frac{dM_b}{dt} = \dot{m}_{PT} - \dot{m}_c \tag{4.12}$$

$$\frac{d\bar{E}_b}{dt} = \dot{m}_{PT} h_{PT} - h_c A_b (T_b - T_{md}) \tag{4.13}$$

where M_b is the bubble mass, $\dot{m}_{PT}$ is the rupture pressure tube primary coolant mass flowrate, $\bar{E}_b$ is the total internal energy of the bubble and h_{PT} is the enthalpy of the primary coolant. Equation (4.13) ignores the effect of the bubble expansion work which is expected to be small.

The hydrodynamics of the fluid forced through the relief pipes are described by the simple system shown in Figure 6. There are N relief pipes of constant flow area A_r, similar to the one shown in the figure. Initially, the moderator fills a small length of the pipe $L_{r,o}$, with the remaining pipe volume filled with an inert gas having a ratio of specific heats γ and at an initial pressure $p_{g,o}$. At the discharge end of each pipe a rupture disc is mounted which has a pressure rating p_{disc}.

As the pressure at the moderator-calandria vessel interface rises, the moderator is accelerated through the relief pipes. The momentum equation for the fluid in a relief pipe can be written as

$$\frac{dv}{dt} = \frac{P_{md} - P_g}{\rho_{md} L_r} - \left(1 + \bar{K} + \frac{fL_r}{d_r}\right) \frac{v^2}{2L_r} - g \qquad (4.14)$$

where v is the moderator velocity in the relief pipe, p_g is the cover gas pressure, $\bar{K}$ is a loss coefficient, d_r is the relief pipe inside diameter, L_r is the moderator column, and g is the gravitational acceleration.

The equation governing the moderator column is given by

$$\frac{dL_r}{dt} = v \qquad (4.15)$$

As the moderator is forced through the relief pipes, it compresses the cover gas. The compression process is assumed to be isentropic resulting in the following relationship.

$$p_g = p_{g,o} \left\{\frac{L_{g,o}}{L_{g,o} + L_{r,o} - L_r}\right\}^{\gamma} \qquad (4.16)$$

where $L_{g,o}$ is the initial cover gas column. The rupture discs are assumed to open instantaneously when $p_g = p_{disc}$. No relief is credited prior to discs rupture.

In order to determine the moderator pressure, we consider the following. The increase in the volume of the expanding bubble must be equal to:

(1) the decrease in volume of the moderator fluid due to its compression,

(2) the decrease in volume of other in-core components (neglected in the present study which is a conservative assumption),

(3) the increase of volume of the vessel due to its flexibility, and

(4) the volume of water expelled through the relief pipes.

Thus, the following equation can be written

$$4\pi\alpha = -\frac{dp_{md}}{dt} F_w + \frac{dp_{md}}{dt} F_v + N v \left(\frac{\pi d_r^2}{4}\right) \tag{4.17}$$

where F_v is the vessel shell flexibility defined by

$$F_v \triangleq \frac{dV}{dp} \tag{4.18}$$

and F_w is the moderator compressibility given by

$$F_w = -\frac{V^2}{c_m^2 M_{md}} \tag{4.19}$$

In Equation (4.19), c_m is the speed of sound in the moderator fluid, and M_{md} is the mass of the moderator fluid.

The volume V in Equations (4.18) and (4.19) is the moderator volume inside the vessel given by the expression

$$V = \frac{4}{3}\pi (r_v^3 - r_b^3) \tag{4.20}$$

Rearranging Equation (4.17) yields

$$\frac{dp_{md}}{dt} = \frac{4\pi\alpha - Nv\left(\frac{\pi d_r^2}{4}\right)}{F_v - F_w} \tag{4.21}$$

The equations of conservation of mass and energy for the moderator fluid are given by

$$\frac{dM_{md}}{dt} = \dot{m}_c - Nv\rho_{md}\left(\frac{\pi d_r^2}{4}\right) \tag{4.22}$$

and

$$\frac{\bar{dE}_{md}}{dt} = h_c A_b (T_b - T_{md}) - Nv\rho_{md} c_{p,md} T_{md} \left(\frac{\pi d_r^2}{4}\right) \tag{4.23}$$

In Equation (4.23) both kinetic and potential energies are neglected. $\bar{E}_{md}$ is the total internal energy of the moderator fluid, and $c_{p,md}$ is its specific heat.

The moderator bulk temperature T_{md} can be found from the relationship

$$\frac{\bar{E}_{md}}{M_{md}} = c_{p,md} (T_{md} - T_o) \qquad (4.24)$$

where T_o is a reference temperature.

(c) Solution

The nine ordinary differential equations (4.7), (4.9), (4.12), (4.13), (4.14), (4.15), (4.21), (4.22) and (4.23), the algebraic equations (4.10), (4.11), (4.12), (4.16), (4.19), (4.20) and (4.24), the equations of state for steam/water and the appropriate initial conditions fully define the transient bulk pressurization problem.

A computer program was developed using the above mentioned formulae. A fourth-order Runge-Kutta method was used to advance the solution to the system of equations.

4.1.2.2.2 A Parametric Study

The model described above in Section 1.2.2.1 has been applied in a parametric study to determine the important parameters which have to be simulated in a smaller size calandria vessel, in order to generate representative pressure transients and characterize in full detail the thermohydraulic phenomena. The important parameters in this study are: i) relief pipe parameters (number of pipes, diameter, length, moderator fluid initial column, cover gas type and initial pressure, and rupture discs rating), ii) system flexibility (calandria shell, moderator fluid, calandria tubes, etc.), iii) bubble condensation, iv) ruptured tube mass flow rate, v) vessel diameter, vi) system pressures (primary coolant and moderator), and vii) system temperatures (primary coolant and moderator).

It is important to maintain the relief pipe parameters prototypical, since they affect the timing of rupture discs opening and since the moderator initial column affects the peak pressure. If the possible shock wave is to be investigated then the system pressures must be prototypical. It is also important to maintain a prototypical primary coolant temperature since it determines the initial bubble pressure. Thus, we are left with four parameters to investigate, specifically items (ii), (iii), (iv) and (v). It should be noted that the effect of the moderator initial temperature is taken into account in the bubble condensation parameter.

For all the test cases, the computer program was executed until the rupture discs opened and the following program parameters were used unless otherwise mentioned:

The Ruptured Pressure Tube

Primary coolant pressure	= 10 MPa
Primary coolant temperature	= 280°C

The Moderator Fluid

Initial pressure	= 0.136 MPa
Initial temperature	= 72°C
Condensation heat transfer coefficient	= 0 $kW/m^2°K$
Speed of sound	= 1500 m/s

The Bubble

Initial radius	= 0.0515 m
Initial bubble pressure	= p_{sat} (280°C)

The Relief Pipes

Number of pipes	= 4
Inside diameter	= 0.484 m
Moderator column	= 0.61 m
Pipe length	= 9.3 m
Cover gas	= helium (γ = 1.66)
Cover gas initial pressure	= 127.6 kPa
Rupture disc rating	= 137.9 kPa

Assumed Reactor Calandria Vessel Parameters

Equivalent spherical diameter	= 7.5 m
Shell flexibility, F_o	= 4.39 E-7 m^5/N*
Initial fluid mass	= 212500 kg

(a) Effect of Shell Flexibility

In this study the transient bulk pressurization model was applied to investigate the effect of the calandria vessel shell flexiblity. The ruptured pressure tube mass flowrate was assumed 130 kg/s. In all the cases presented here, the assumed reactor calandria vessel dimensions and moderator fluid mass were used, however, the shell flexibility was varied. Three cases were studied: (i) prototypical** flexibility $F_v = F_o$, (ii) twice the prototypical flexiblity $F_v = 2F_o$, and (iii) one-half the prototypical flexiblity $F_v = 1/2\ F_o$. Figure 7 displays the predicted time history of the bubble pressure (only for the first case), calandria pressure, bubble radius and moderator column in the relief pipes until the rupture discs open. A brief analysis of the results is presented below.

(i) Prototypical Flexibility

The predictions are shown by solid lines in Figure 7. The following are the main conclusions:

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* This value assumes no end shield motion which is a conservative assumption and was used previously in Ref. [6]. A typical CANDU shell flexibility with end shield motion is calculated to be 6.23E-$7m^5$/N. The presence of any gas space in the calandria vessel will affect the flexiblity.

** Prototypical refers to assumed reactor parameters.

(1) The calandria pressure rises rapidly to a maximum of 0.99 MPa after 19 ms from rupture. The pressure then oscillates with both the amplitude and minimum pressure decaying. The frequency of oscillations is about 26 Hz.

(2) The pressure inside the bubble decreases rapidly to a minimum of 0.35 MPa. The bubble pressure then oscillates, however, it is almost 180° out of phase with respect to the calandria pressure.

(3) The bubble expands in stages. During the initial calandria pressure rise the bubble rapidly expands to a radius of 0.47 m then stays almost constant while the calandria pressure is decreasing (actually a slight decrease in radius occurs). This bubble expansion behaviour is repeated for each pressure oscillation, however, the expansion rate decreases with time.

(4) The moderator column in the relief pipes rises relatively slowly in the first 20 ms, then a nearly constant rate of rise is achieved. The rupture discs open after 140 ms.

(ii) Other Flexiblities

The predictions for $F_v = 2F_o$ and $F_v = 1/2\ F_o$ are also shown in Figure 7. The main conclusions are:

(1) The maximum calandria pressure and the frequency of oscillations increase as the flexibility decreases.

(2) The bubble expands to a smaller radius in the initial expansion phase as the flexibility decreases, however, the effect of flexibility diminishes with time.

(3) The rupture discs open faster as the flexibility decreases.

From the above discussions it is seen that representative generation of the thermohydraulics associated with transient bulk pressurization requires maintaining a representative shell flexibility. In fact, the additive effect of the flexibility of all in-core components must be maintained.

(b) Effect of Bubble Condensation

The effect of bubble condensation was investigated by varying the condensation heat transfer coefficient h_c. In all the cases studied here, the reactor calandria vessel parameters were used and the ruptured pressure tube mass flowrate was assumed 130 kg/s. Three cases were analyzed (i) $h_c = 0$, (ii) $h_c = 500$ kW/m^{2}K and (iii) $h_c = 2500$ kW/m^{2}K. The latter value of h_c was mentioned in Reference [1] as a plausible value for use in the equations governing the bulk pressurization phenomenon in the moderator.

The predictions for these three cases are shown in Figure 8. The following conclusions can be drawn:

(1) The maximum calandria pressure and the frequency of oscillations decrease with the increase of the condensation heat transfer coefficient. Also, the decay in pressure is more rapid.

(2) As the condensation heat transfer coefficient increases, the bubble expands to a smaller radius. In addition, the rate of bubble expansion becomes smaller with time. At the instant of rupture disc opening, the bubble radius is 0.75 m for h_c = 0, 0.7 m for h_c = 500 kW/m^{2}K, and 0.57 m for h_c = 2500 kW/m^{2}K, respectively.

(3) The opening of the relief pipe rupture discs is delayed as h_c is increased.

In conclusion it is seen that bubble condensation significantly affects transient bulk pressurization. Consequently, both the initial bulk moderator temperature in the scaled calandria vessel and the primary coolant temperature must be representative temperatures (typical reactor temperatures).

(c) Effect of Ruptured Tube Mass Flowrate

The effect of the ruptured tube mass flowrate was studied. Figure 9 displays the resulting predictions. In all cases, the reactor calandria vessel parameters were used. Three mass flow rates were investigated, specifically, 130 kg/s, 200 kg/s and 280 kg/s. The second value is the maximum expected discharge flow rate as indicated in Section 3.2..

From the predictions shown in Figure 9, the following can be concluded:

(1) The maximum calandria pressure increases with the increase in the discharge mass flowrate. The frequency of pressure oscillations is not affected.

(2) The bubble expands to a larger radius as the discharge mass flowrate is increased.

(3) The relief pipe rupture discs open faster as the discharge mass flowrate is increased.

In conclusion, a representative transient bulk pressurization requires a prototypical discharge flow rate. This can be achieved by having prototypical (i) pressure-time history in the headers (or the vessel(s) simulating the headers), (ii) end fitting assemblies, (iii) feeders and (iv) burst pressure tube and fuel. The last three parameters ensure having prototypical hydraulic resistance, thermal storage and heat transfer. Since the peak calandria pressure increases with increasing mass flowrate, the hydraulic resistance of the feeders connected to the test burst channel should be equal to that of the feeders having the lowest hydraulic resistance. This ensures achieving the highest possible break mass flowrate.

(d) Effect of Calandria Vessel Diameter

The effect of scaling the vessel diameter has been investigated. Two cases were studied (i) the reference case using the reactor calandria vessel, and (ii) a vessel of diameter 3.35 m (equivalent spherical diameter of 4.27 m). In the latter case the flexibility of the shell was assumed equal to that of the reactor shell plus the difference in flexibility due to the difference in moderator fluid mass (40,000 kg in the small vessel as opposed to 212,500 kg in the reactor). In both cases the ruptured tube mass flowrate was assumed 130 kg/s.

Figure 10 displays the predictions. The main conclusions are as follows:

(1) The maximum calandria pressure is virtually identical in both cases, however, for the smaller vessel the amplitudes of the pressure oscillations following the peak pressure are slightly less (94% of the prototypical), and the frequency of pressure oscillations is higher (107% of the prototypical).

(2) The bubble-radius time history is practically identical.

(3) The moderator column transient in the relief pipes, and the rupture disc opening times are practically identical in the two cases studied.

In conclusion, representative transient bulk pressurization can be generated in a smaller diameter vessel. However, the frequency of pressure oscillations will be slightly higher, and the amplitude slightly smaller.

4.1.3 Bulk Temperature Rise (Long-term Phenomenon)

4.1.3.1 Reactor Calandria Vessel

In less than 1 s following the pressure tube rupture, a pressure plateau is expected to be reached [11]. However, the bulk moderator temperature continues to rise due to the continuous addition of the higher enthalpy primary coolant. When the shut-off-rods are inserted into the reactor, the freed capacity of the moderator cooling circuit is greater than the heat addition and the moderator temperature will decrease.

In order to study the bulk temperature rise phenomenon a simplified model is presented below. Figure 11 shows a schematic of the system under consideration. During the initial tens of milliseconds (~ 150 ms) after the pressure tube rupture, a large quantity of the moderator fluid is expelled through the relief pipes. At the end of this period the pressure stabilizes, and the discharge flow through the relief pipes $\dot{m}_r$ can be assumed steady and equal to the rupture primary coolant mass flowrate $\dot{m}_{pT}$. The moderator cooling circuit is a closed one, thus the moderator inlet flow $\dot{m}_{md,i}$ is equal to the moderator exit flow $\dot{m}_{md,e}$. This means that the moderator fluid mass in the calandria vessel M_{md} can be assumed constant.

Under normal operating conditions, the moderator cooling circuit is used to moderate the fast neutrons and the bulk moderator temperature T_{md} is kept constant. Since we are only interested in the temperature rise above the constant operating temperature, we will assume that the moderator circuit and the moderation heat form an isolated system.

The energy equation for the reactor vessel can thus be expressed by the equation

$$\frac{d}{dt}(M_{md}\, e_{md}) = \dot{m}_{PT}\, h_{PT} - \dot{m}_r\, h_{md} \qquad (4.25)$$

where e_{md} and h_{md} are the moderator internal energy and enthalpy, respectively, and h_{PT} is the ruptured pressure tube primary coolant enthalpy.

Applying the assumptions mentioned above, Equation (4.25) yields

$$\frac{d}{dt}(e_{md}) = \frac{\dot{m}_{PT}}{M_{md}}(h_{PT} - h_{md}) \qquad (4.26)$$

For assumed reactor operating conditions of M_{md} = 212500 kg and T_{md} = 72°C, Equation (4.26) was numerically solved for a discharge period of 120 s. Figure 12 displays the resulting bulk temperature rise transients for three postulated ruptured pressure tube primary coolant mass flowrates namely, 130 kg/s, 200 kg/s and 280 kg/s. The primary coolant thermodynamic conditions are assumed to be 10 MPa pressure and 280°C temperature.

4.1.3.2 Scaled Calandria Vessel

Since the scaled calandria vessel is smaller in size than that of the reactor calandria vessel, the moderator fluid mass inside the scaled vessel is less than that in the reactor vessel. With no moderator cooling circuit, the bulk fluid temperature will, of course, rise at a faster rate than that in the reactor, under the same conditions, as can be shown from Equation (4.26).

In order to simulate the predicted bulk moderator temperature rise in the reactor, a moderator cooling circuit must be connected to the scaled calandria vessel. For a given cooling water inlet temperature $T_{cool,i}$, the mass flowrate must be calculated such that the scaled calandria vessel temperature rise would be the same as the corresponding predicted rise in the reactor vessel under the same conditions. An energy equation similar to Equation (4.26) with the addition of the moderator cooling terms can be expressed as

$$\frac{d}{dt}(M_{md,sv}\, e_{md,sv}) = \dot{m}_{PT}\, h_{PT} - \dot{m}_r\, h_{md,sv} + \dot{m}_{cool}(h_{cool,i} - h_{md,sv}) \qquad (4.27)$$

where $M_{md,sv}$, $e_{md,sv}$ and $h_{md,sv}$, are the scaled vessel moderator fluid mass, internal energy and enthalpy, respectively, and $h_{cool,i}$ is the moderator fluid inlet enthalpy.

Equation (4.27) assumes that the cooling water outlet mass flowrate is equal to the inlet mass flowrate ($\dot{m}_{cool}$). This is a necessary requirement in order to minimize the disturbances caused by the moderator cooling water circulation.

Using the assumptions of Section 4.1.3., Equation (4.27) can be rearranged to yield

$$\dot{m}_{cool} = \frac{\dot{m}_{PT}\,(h_{PT} - h_{md,sv}) - M_{md,sv}\,\dfrac{d(e_{md,sv})}{dt}}{(h_{md} - h_{cool,i})} \qquad (4.28)$$

For small time intervals, Equation (4.28) can be approximated by

$$\dot{m}_{cool} \simeq \frac{\dot{m}_{PT}\,(h_{PT} - h_{md,sv}) - M_{md,sv}\,\dfrac{\Delta e_{md,sv}}{\Delta t}}{(h_{md} - h_{cool,i})} \qquad (4.29)$$

Equation (4.29) was numerically solved to calculate the necessary cooling water mass flowrate under the same primary coolant thermodynamic conditions mentioned in Section 4.1.3.1, specifically, p_{PT} = 10 MPa and T_{PT} = 280°C. The scaled calandria vessel fluid mass and initial temperature were $M_{md,sv}$ = 40,000 kg and $T_{md,sv,i}$ = 72°C respectively. The scaled vessel moderator fluid mass was chosen as 40,000 kg in order to keep the necessary cooling water requirements, and the scaled vessel size within reasonable bounds. This mass corresponds to a scaled vessel inner diameter of 3.35 m.

Figure 13 displays the cooling water mass flowrate requirements for a ruptured pressure tube mass flow rate of 130 kg/s, and for three cooling water inlet temperatures namely, 20°C, 30°C and 40°C. The figure also displays (the solid line) the moderator bulk temperature rise which is identical to the predicted reactor temperature rise under the given conditions. Figures 14 and 15 display similar information but for ruptured pressure tube mass flow rates of 200 kg/s and 280 kg/s respectively.

In conclusion, representative generation of the bulk temperature rise phenomenon can be achieved in a scaled vessel provided proper moderator cooling is taken into account.

Eight nozzles (four on each side of the vessel) designed to deflect the cooling water upwards with a velocity of approximately 2 m/s [24] should be provided in the scaled calandria vessel. The nozzle area will, of course, depend on the cooling flow rate requirements. These conditions are similar to those in a typical CANDU reactor.

4.1.4 Conclusions and Recommendations

Representative generation of pressure transients as well as characterization of the thermohydraulic phenomena can be achieved in a scaled calandria vessel provided that:

(a) The sum of the flexibility of the scaled vessel plus the flexibility of its moderator fluid is equal to the corresponding sum in a typical CANDU reactor.

(b) During the test, the scaled vessel moderator fluid temperature rise is to be maintained equal to the predicted temperature rise in a typical CANDU reactor, under the same nominal conditions. This can be achieved by using a moderator cooling circuit.

The following recommendations are made with regards to the scaled calandria vessel.

(a) The scaled vessel inner diameter should be 3.35 m. For a design pressure of 1.38 MPa and design temperature of 149°C, the shell thickness is 19.05 mm, according to the ASME Pressure Vessel Code. The vessel head thickness, corresponding to the reactor face, is 140 mm.

Since the scaled vessel (smaller diameter)/moderator fluid (less fluid mass) system is stiffer than the corresponding system in a typical CANDU reactor, a flexible medium having a flexibility (i.e. dV/dp) equal in magnitude to the difference in flexibility of the shell plus the moderator fluid is required to be installed inside the vessel to compensate for the loss in flexibility. In fact, provision for additional flexibility to account for calandria tube flexibility should be made. However, this is a relatively small value.

(b) A moderator cooling circuit must be used. However, in order to avoid the cost of a large heat exchanger, an open circuit can be used, provided that the cooling water exit and inlet mass flowrates are maintained equal. Since a pressure plateau is expected to be reached in less than 1 s following rupture, a standpipe connected to the bottom of the calandria vessel will ensure equal flows. The inlet mass flowrate should be automatically controlled to provide the necessary cooling water requirements.

In order to avoid disturbing the short-term thermohydraulic phenomena, the moderator cooling circuit should not be initiated until the relief pipes rupture discs have opened.

More details will be given in the test facility specifications.

4.2 The Shut-off-rod Guide Tubes (SORGTs)

A smaller diameter calandria vessel implies shorter shut-off-rod guide tubes, relative to those in a typical CANDU reactor. Full size SORGTs with prototypical end conditions can be used by connecting pipes above and below the test vessel. However, such a design would make the test vessel bulky, complicate the vessel support, require considerable over-head space in the test site, and increase the cost of the facility and replacement of the SORGTs.

It is important to maintain the geometry of the rods (except for the length) and their relative location in the tube lattice identical to that in a typical CANDU reactor. However, in order to have representative SORGT dynamic response to the generated loadings, and since the scaled SORGTs are shorter relative to those of the CANDU reactor, it is necessary to modify the end conditions of the scaled SORGT. Below, analysis for the scaled SORGT is presented.

4.2.1 The Scaled SORGT

Recognizing that both the mass and stiffness cannot simultaneously be maintained prototypical for a shorter SORGT, we have chosen to maintain prototypical first mode natural frequency and rod geometry (except for the length).

A typical CANDU reactor SORGT consists of a long perforated tube [1] which has fixed-hinged end conditions, as shown schematically in Figure 16 (a). The natural frequency for the first mode is given by [25]

$$\omega_1 = 15.4 \sqrt{\frac{EI}{mL^4}} \tag{4.30}$$

where I is the second moment of area, m is the weight per unit length, L is the length, and E is the modulus of elasticity.

In order to satisfy the above requirements, it is proposed to connect two identical virtually massless lateral springs, of stiffness K, each to one end of the SORGT, as shown schematically in Figure 16(b).

4.2.2 The Governing Equation and Solution

In order to determine the required spring stiffness K, the scaled SORGT is analyzed below. Consider the Euler equation for the beam [26].

$$\frac{d^4y}{dx^4} - \beta^4 y = 0 \tag{4.31}$$

where

$$\beta^4 = m \left(\frac{\omega^2 1}{EI}\right) , \tag{4.32}$$

and x and y are the distance along the beam and the deflection, respectively.

The solution to Equation (4.31) is given by

$$y = A \cosh \beta x + B \sinh \beta x + C \cos \beta x + D \sin \beta x \qquad (4.33)$$

where A, B, C and D are constants.

Consider Figure 16(b). The boundary conditions are

$$\text{At } x = \frac{L}{2} \qquad EI \frac{d^3y}{dx^3} = -Ky \qquad \text{(Force exerted by SORGT = Force exerted by spring)} \qquad (4.34)$$

and

$$EI \frac{d^2y}{dx^2} = 0 \qquad \text{(Bending moment = 0)} \qquad (4.35)$$

$$\text{At } x = -\frac{L}{2} \qquad EI \frac{d^3y}{dx^3} = -Ky \qquad \text{(Force exerted by SORGT = Force exerted by spring)} \qquad (4.36)$$

and

$$EI \frac{d^2y}{dx^2} = 0 \qquad \text{(Bending moment = 0)} \qquad (4.37)$$

Substituting Equation (4.33) into the boundary condition (4.34) yields

$$EI\,\beta^3 \left(-A \sinh \beta\tfrac{L}{2} + B \cosh \beta\tfrac{L}{2} - C \sin \beta\tfrac{L}{2} - D \cos \beta\tfrac{L}{2}\right) =$$

$$-K \left(A \cosh \beta\tfrac{L}{2} - B \sinh \beta\tfrac{L}{2} + C \cos \beta\tfrac{L}{2} - D \sin \beta\tfrac{L}{2}\right) \qquad (4.38)$$

Similary the boundary conditions (4.35), (4.36) and (4.37), respectively, become

$$EI\,\beta^2 \left(A \cosh \beta\tfrac{L}{2} + B \sinh \beta\tfrac{L}{2} - C \cos \beta\tfrac{L}{2} - D \sin \beta\tfrac{L}{2}\right) = 0 \qquad (4.39)$$

$$EI\,\beta^3 \left(A \sinh \beta\tfrac{L}{2} + B \cosh \beta\tfrac{L}{2} + C \sin \beta\tfrac{L}{2} - D \cos \beta\tfrac{L}{2}\right) =$$

$$-K \left(A \cosh \beta\tfrac{L}{2} + B \sinh \beta\tfrac{L}{2} + C \cos \beta\tfrac{L}{2} + D \sin \beta\tfrac{L}{2}\right) \qquad (4.40)$$

and

$$EI\,\beta^2\,(A\cosh\beta\tfrac{L}{2} - B\sinh\beta\tfrac{L}{2} - C\cos\beta\tfrac{L}{2} + D\sin\beta\tfrac{L}{2}) = 0 \qquad (4.41)$$

Equations (4.38), (4.39), (4.40) and (4.41) can be algebraically manipulated to yield

$$C = A\left(\frac{\cosh\beta\frac{L}{2}}{\cos\frac{L}{2}}\right) \qquad (4.42)$$

$$D = B\left(\frac{\sinh\beta\frac{L}{2}}{\sin\beta\frac{L}{2}}\right) \qquad (4.43)$$

$$\left(\frac{EI\beta^3}{2K}\right)\left(B\cosh\beta\tfrac{L}{2} - D\cos\beta\tfrac{L}{2}\right) = -A\cosh\beta\tfrac{L}{2} \qquad (4.44)$$

$$\left(\frac{EI\beta^3}{2K}\right)\left(A\sinh\beta\tfrac{L}{2} + C\sin\beta\tfrac{L}{2}\right) = -B\sinh\beta\tfrac{L}{2} \qquad (4.45)$$

The above equations can be solved for the stiffness K to yield

$$K = \frac{EI\beta^3}{2}\left\{\left(1 - \frac{\sinh\beta\frac{L}{2}\cos\beta\frac{L}{2}}{\cosh\beta\frac{L}{2}\sin\beta\frac{L}{2}}\right)\left(1 + \frac{\cosh\beta\frac{L}{2}\sin\beta\frac{L}{2}}{\sinh\beta\frac{L}{2}\cos\beta\frac{L}{2}}\right)\right\}^{\frac{1}{2}} \qquad (4.46)$$

In order to calculate the required spring stiffness K, the value of β has to be calculated. This is achieved by equating the natural frequency of a typical CANDU SORGT from Equation (4.30) to the natural frequency of the scaled SORGT from Equation (4.32). Thus,

$$\beta^2\left(\frac{EI}{m}\right)^{\frac{1}{2}} = \frac{15.4}{L^2}\left(\frac{EI}{m}\right)^{\frac{1}{2}}$$

Thus, for an assumed SORGT length of 7.1 m,

$$\beta = (15.4)^{1/2}/(7.1) = 0.5527 \qquad (4.47)$$

From the scaled vessel diameter considerations, the scaled SORGT length, L_{sc} is chosen as

$$L_{sc} = 2.9 \text{ m} \tag{4.48}$$

Substituting the values of , L, I and E (the two latter parameters were calculated using information contained in Reference [12]) into Equation (4.46) yields

$$K = 5697.0 \text{ N/m}^* \tag{4.49}$$

4.2.3 The Design of End Springs

Figure 17 shows a schematic of the proposed springs and scaled SORGT/vessel assembly. Two identical cantilever springs each constructed from a cylindrical solid rod are proposed to be used. This arrangement provides representative lateral stiffness in all bending directions. It should be noted that the design should limit the axial travel so that grossly deformed SORGT's would not pull off the springs.

From the scaled vessel diameter, and the scaled SORGT length considerations, the rod length, L_s is chosen to be

$$L_s = 175 \text{ mm} \tag{4.50}$$

The cylindrical-cantilever stiffness K is given by [26]

$$K = \frac{3E_s \pi d_s^4}{64 L_s^3} \tag{4.51}$$

where d_s is the cantilever diameter and E_s is its modulus of elasticity.

Assuming a stainless steel rod (E_s = 19.3E10 Pa), the dimensions (4.48) and (4.50) can be substituted into Equation (4.51) to yield

$$d_s = 10.15 \text{ mm} \tag{4.52}$$

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* If one models the stiffness of the SORGT only, it can be shown that a typical CANDU SORGT's stiffness is 21.7 kN/m. Considering the scaled SORGT as a simply supported beam, its stiffness is 139.3 kN/m. These two values were arrived at assuming the beams to be centrally loaded. Thus, in order to maintain a prototypical stiffness, each end spring should have a stiffness of 12.8 kN/m. Since this is stiffer than calculated in equation (4.49), the latter value, i.e. the value resulting from maintaining a prototypical natural frequency for the first mode, is considered more appropriate.

4.3 Simulated Fuel Channels

The simulated dummy channels should have real calandria tubes. However, for cost saving purposes, the pressure tube and the fuel may be simulated such that representative dynamic response can be achieved under the generated loadings.

4.3.1 Simulated Pressure Tubes

The simulated pressure tubes should be made from mild steel. The tube outside diameter should be the same as that of a typical CANDU reactor pressure tube. For example, the following are the specifications of a CANDU-600 pressure tube [2,3].

Material	= zirconium-niobium 2.5% wt
Modulus of elasticity, E_{ZrNb}	= 9.4E10 Pa
Density, ρ_{ZrNb}	= 6489 kg/m^3
Outside diameter	= 111.78 mm
Wall thickness, Δt	= 4.19 mm
Length	= 6299.0 mm

The second moment of area I is given by

$$I_{PT} = \pi r^3_{avg} \Delta t$$
$$= \pi(0.053795)^3(0.00419)$$
$$= 0.2049E\text{-}5 \text{ m}^4$$

In order to maintain the annulus gap between the calandria tube and the pressure tube unchanged, the mild steel pressure tubes must have the same outer diameter as the real ones. The relevant mild steel properties are

$$E_{ms} = 19.305E10 \text{ Pa}$$
$$\rho_{ms} = 7870 \text{ kg/m}^3$$

In order to ensure representative dynamic response, the following two conditions are necessary

$$E\ I = \text{constant} \tag{4.53}$$

$$\text{Mass of pressure tube and internals} = \text{constant} \tag{4.54}$$

The first condition can be used to determine the inside diameter $d_{i,ms}$ of the simulated pressure tube, as follows

$$(E\ I)_{PT,ms} = (E\ I)_{PT,ZrNb} \tag{4.55}$$

upon substituting the relevant values, Equation (4.55) yields

$$d_{i,ms} = 0.10795 \text{ m}$$

Thus, the wall thickness of the mild steel pressure tube is 1.92 mm.

4.3.2 Simulated Fuel Mass

In order to satisfy the second condition (4.54), the simulated fuel mass must be equal to the mass of the real fuel bundles plus the mass of the channel water inventory plus the mass difference between the real pressure tube and the mild steel pressure tube.

Each channel has 12 bundles [3] each weighing 23.5 kg, thus

Mass of fuel bundles = (12)(23.5) = 282.0 kg.

The mass of channel water inventory is 15.9 kg.

The mass difference between real pressure tube and simulated pressure tube is

$$\text{Pressure tubes mass difference} = 2\pi L[(R\Delta t)_{ZrNb} - (R\Delta t)_{ms}]$$

$$= 25.0 \text{ kg}$$

Thus,

Total simulated fuel mass = (282 + 15.9 + 25.0) = 322.9 kg.

It is desirable to have the same number of simulated fuel 'bundles', each having prototypical length (0.495 m [3]). If solid mild steel cylinders are used, the cylinder diameter can be obtained from

$$\text{Mass of each cylinder} = \frac{322.9}{12} = \frac{\pi}{4} d^2_{ms}\ L\ \rho_{ms}$$

$$26.91 = \frac{\pi}{4} d^2_{ms}\ (0.495)(7870)$$

Thus, each simulated fuel 'bundle' diameter, is $d_{ms} = 0.09378$ m

Each cylinder should have bearing pads such that their number, shape and bearing surface diameter to simulated pressure tube inside diameter clearance be prototypical.

5. BURST CHANNEL

5.1 Channel Design Considerations

Since the temperature of the primary coolant in the burst pressure tube is high (up to 300°C), and in order to prevent moderator water boiling, the burst pressure tube must be insulated. The possibility of insulating the pressure tube without the presence of a calandria tube has been investigated. No suitable insulating material which will not affect the burst has been found. Thus, it is recommended to use a real calandria tube with the pressure tube/calandria tube annulus being nitrogen filled to provide thermal insulation. In order to prevent pressure relief, during pressure tube burst, through the channel annulus bellows, the burst channel should have no bellows. However, provision for bleeding up to 10 l/s of water from the annulus during pressure tube rupture should be made. The calandria tube should be weakened in such a way that it will rupture following the pressure tube burst, and will not interfere with long term damage mechanisms. The presence of a calandria tube is necessary, as well, for the recommended burst initiation method as discussed in Section 5.3.

5.2 Pressure Tube Burst Mode

As discussed in Reference [1], an axial split is generally considered to have more damaging potential as opposed to a circumferential split. This conclusion was arrived at based on both experimental and analytical evidence. It is thus recommended that the test burst pressure tube be weakened axially, to cause an axial split.

5.3 Burst Initiation Method

Several methods were considered for the purpose of initiating the pressure tube rupture. These methods are discussed below.

(a) The use of an explosive device such as a thermite bomb [1] which will cause failure by melting. Such a method was ruled out since external energy is added to the system making it unrepresentative.

(b) The use of a local spark electrode. Previous experience at Westinghouse Canada Inc. indicated that such a method would not produce the desired axial failure, but rather local melting resulting in a small hole.

(c) An axial defect of desired length is milled in the outer wall of the pressure tube. The depth of the defect would be such that rupture does not occur until a specified pressure is reached (up to 11 MPa). In addition, axial defects of desired length are milled in the outer wall of the calandria tube. During loop warm-up, a relatively higher than normal pressure tube/calandria tube annulus pressure is maintained (up to 2 MPa) using nitrogen gas. However, the annulus pressure must be less than that which will cause premature rupture of the calandria tube. When test conditions are obtained, the system pressure is raised just above the burst pressure of the pressure tube and the annulus pressure is reduced until failure of the pressure tube occurs. This should be followed by the calandria tube failure. Provision should be made in the pressurizing system for instantaneous pressure spikes to cause pressure tube

rupture, should the depressurization of the annulus not suffice. This method has been previously used with success at Westinghouse Canada Inc. with a scatter of 0.5 MPa and a sample of three.

It is recommended that the last method, Section 5.3 (c), be used since it has been successfully used previously and no extra energy is added to the system. It is also recommended that at least two bench tests be carried out to demonstrate bursting pressure of the defected pressure tube within $\pm$ 1 MPa of specified burst pressure.

6. THE PROPOSED TEST FACILITY

6.1 Test Loop

The proposed test loop is shown schematically in Figure 18. The loop consists of a high pressure/high temperature warm-up loop (operating conditions: light water at 11 MPa (1595 psia) and 300°C (572°F)) shown by heavy lines, and a low pressure/low temperature moderator loop (operating conditions: light water at 1.38 MPa (200 psia) and 149°C (300°F)) shown by light lines.

In the warm-up loop, water flows from a separator to a circulating pump (capable of operating at up to 32 l/s). Downstream of the pump is a venturi flowmeter station, a control valve V-1 and a suitable boiler. From the boiler the water is piped to a supply vessel(s)*. The water then flows from the vessel(s) through a piping network identical to a typical CANDU reactor inlet feeder+, or of equivalent hydraulic resistance. A venturi flowmeter station is to be installed in this line near the supply vessel(s) outlet. The water then flows through the Burst Pressure Tube (BPT) located in the test calandria vessel. The water exiting from the BPT flows through a piping network either identical to a typical CANDU outlet feeder or of equivalent hydraulic resistance. This piping network goes back to the supply vessel(s). In this line there is a control valve V-3 and a venturi flowmeter station. At some point in the outlet feeder (as shown in Figure 19), the water flows back to the separator through a control valve V-4. A by-pass line with a control valve V-5 connects the separator to the pipe connecting the boiler and the supply vessel(s). The latter pipe has a control valve V-2 in it. Provision is also required for pressurizing two more channels (known as the Target Channels) during warm-up, with minimal circulation.

In the moderator loop water flows from a 'Cooling Water Tank' through a pneumatic valve V-6 to a circulating pump. The water then flows through a venturi flowmeter station, a pneumatic control valve V-7 and a water preheater. The water then is directed to the 'Test Calandria Vessel' through a set of eight nozzles, four on each side of the vessel. The water exits from the bottom

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* The supply vessel(s) can be one or several. Also, the supply vessel(s) outlet may be branched directly to the two feeders, or separate supply vessels may be connected separately to each feeder. These alternatives, or any other suitable alternative, are discretionary.

\+ The details of all components are listed in Chapter 7.

of the vessel through a 24" STD* standpipe which contains an orifice flowmeter station and a pneumatic control valve V-8. The standpipe discharges the water into a 'Catch Tank'. A by-pass pipe with a pneumatic control valve V-9 connects the standpipe to the circulating pump inlet as shown in Figure 18.

6.2 Test Section

The test section consists of a 43 m^3 (1516 ft^3) 'Test Calandria Vessel', the details of which are shown in Figure 19. Four 18" STD relief pipes each having a 0.14 MPa (20 psi) rupture disc at the discharge end of the pipe are connected to the top of the vessel. The discharge from these pipes (during testing) is directed towards the 'Catch Tank'.

Provision is to be made for a square array (5 x 5 array with no corner channels) of up to 21 pressure tube/calandria tube (PT/CT) assemblies. This array includes one BPT, up to two 'Target PT/CT', and up to 18 'Dummy PT/CT' assemblies.

Provision must be made for an arrangement of up to 11 vertical 'Shut-off-rod Guide Tubes' (SORGTs), and one Adjuster Rod assembly. Figure 19 shows the possible locations.

6.3 Auxiliary Systems

Systems for pressurizing the relief pipes with helium at 27.6 kPa gauge (4 psig) as cover gas, for pressurizing or depressurizing the burst channel PT/CT annulus with nitrogen (maximum 2 MPa (290 psia)), and for bleeding of up to 10 l/s of water during pressure tube rupture from the BPT annulus, are required.

The 'Target PT/CT' assemblies (up to two) require provision for pressurizing them with hot water at the required BPT conditions with minimal circulation. The annuli of these PT/CT assemblies will be nitrogen filled at 0.1 MPa with minimal circulation.

Since the 'Test Calandria Vessel' is smaller in diameter than the corresponding CANDU reactor vessel, it is necessary for simulation, as indicated in Section 4.1.4, to install, inside the Test Calandria Vessel, a flexible medium such that the flexibility (i.e. dV/dp) of the test calandria vessel and internals (mainly the moderator fluid) is approximately equal to the corresponding flexibility of a typical CANDU reactor (approximately 7.2E-7m^3/N). How this is achieved is optional. For example, properly designed and evenly distributed air compartments may be used.

6.4 Test Procedure

During warm-up, both valves V-3 and V-5 (Figure 18) are closed and the high pressure/high temperature loop is brought up to test conditions. The supply vessel(s) is filled with the proper water inventory. Two options for the discharge duration through the BPT are to be considered: i) a short duration option of 60 s, and ii) a long duration option of 120 s. In both cases the maximum expected rupture flow rate is 200 kg/s.

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* Standard pipe size.

In the moderator loop both valves V-6 and V-8 are closed. The water is circulated through the Calandria Test Vessel and the water preheater is used to bring the water temperature in the vessel to approximately 72°C (162°F). In the relief pipes, the water level is set at approximately 0.6 m (2 ft.), and the cover gas pressure at 27.6 kPa gauge (4.0 psig).

When test conditions are attained, valves V-2 and V-4 are closed, the boiler power is switched off and valves V-5 and V-3 are opened. The moderator loop is maintained as it was during the warm-up stage, and the pressure tube burst initiation procedure, (discussed in Section 5.3) started. Upon burst initiation, the moderator fluid will be forced into the relief pipes, thus compressing the cover gas. When the cover gas pressure reaches the rating of the rupture discs, the rupture discs will open. This signals (through an appropriate signaling system) valves V-6 and V-8 to open, valve V-9 to close, and the preheater power to be switched off, allowing cooling water to circulate through the calandria vessel. Valve V-7 must automatically vary to control the cooling water flow rate in order to maintain the temperature rise of the moderator water equal to the predicted corresponding rise in a typical CANDU moderator vessel under the same nominal conditions as discussed in Section 4.1.3.2. (Figure 14 shows the predicted bulk moderator temperature rise for a 200 kg/s rupture flow rate at 280°C. The figure also displays the required scaled vessel moderator cooling water flow rate at three different temperatures, specifically 20°C, 30°C and 40°C.)

During discharge (in either the 60 s option or the 120 s option), a specific pressure-time history in the supply vessel shall be maintained (as mentioned in Section 3.2). Figure 5 shows a reference example for such a history. Provison must be made for other pressure-time histories, specifically for a higher initial pressure (11 MPa) decreasing with time at the given slope for the reference example, or at a steeper slope. The method to be used is optional.

During the test the post rupture behaviour shall be recorded using high speed video cameras through the special windows provided in the vessel wall.

7. TEST FACILITY COMPONENT SPECIFICATIONS

In this section the detailed specifications of the major components of the test facility are listed.

7.1 The Test Calandria Vessel

7.1.1 Main Features

The test calandria essel is a 43 m^3 cylindrical vessel. Figure 19 shows the major components and dimensions of the scaled calandria vessel. The vessel has penetrations for i) four relief pipes, ii) eleven SORGTs, iii) one adjuster rod assembly, iv) six lighting and photography ports, v) eight moderator cooling inlet nozzles (four on each side), vi) two moderator cooling exit pipes, vii) a man hole, viii) an access hole to remove damaged pressure tube/calandria tube assemblies, ix) two pipes for helium balance and vessel drainage, and x) twenty-one full-size pressure tube/calandria tube assemblies.

Other vessel designs are permitted but the following are the main design specifications which must be met:

Design Pressure	1.38 MPa (200 psia)	
Design Temperature	149°C (300°F)	
Material	SA516 Gr. 70	Head and Shell
Volume	43 m^3 (1516 ft^3)	
Inside Diameter	3.35 m	
Inner Length	5.8138 m	
Shell Thickness	19.05 mm (min.)	
Head* Thickness	140.0 mm (min.)	
Head* Diameter	1.625 m (min.)	
Channel Penetrations (Number of)/Diameter	21/142.24 mm dia.	Square Lattice, at 286 mm Pitch, with no Corner Channels
Shut-off-rod Guide Tube Penetrations/Diameter	12/128 mm dia.	Vertical
Relief Pipe Penetrations/ Diameter	4/438.0 mm (18" STD)	Vertical
Standpipe Penetrations/ Diameter	2/438.0 mm+ (18" STD)	Vertical
Moderator Cooling Inlet Nozzle Penetrations/Diameter	8/154.1 mm (6" STD)	Four on each side
Viewing and Lighting Penetrations/Diameter	6/154.1 mm (6" STD)	
Manhole Penetration/ Diameter	1/590.6 mm (24" STD)	
Access Penetration/ Diameter	1/254.5 mm (10" STD)	

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* "Reactor Face".

\+ Reinforcement may be necessary on all 18" and 24" penetrations.

Equalizing and/or Draining Penetrations/Diameter	3/52.5 mm (2" STD)	Two from top/one from bottom
Moderator Inlet Deflecting Nozzles	8	Made of 6.35 mm Stainless Steel Plate
Required Total Flexibility of the Test Calandria Vessel Plus Moderator Fluid	7.2E-7 m^5/N	Discussed in Section 4.1.4. This value accounts for the shell flexibility plus the moderator fluid flexibility.

7.1.2 Fittings*

		Quantity
Welding Neck Flange	5" - 150#	12
Blind Flange	5" - 150#	12
Welding Neck Flange	6" - 150#	6
Blind Flange	6" - 150#	6
Welding Neck Flange	10" - 150#	1
Blind Flange	10" - 150#	1
Welding Neck Flange	24" - 150#	1
Blind Flange	24" - 150#	1
Flexitallic Gaskets	5" - 150#	12
Flexitallic Gaskets	6" - 150#	6
Flexitallaic Gaskets	10" - 150#	1
Flexitallic Gaskets	24" - 150#	1
Tempered Sight Glass	5" dia. - 1" thick	6
Calandria Tube O-Ring	~ 5.185" I.D.	42
End Fitting O-Ring	~ 5.75" I.D.	6
Outside Flange O-Ring	~ 7.0" I.D.	6

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* All custom made flanges fixed to the channels are not included in this section. However, possible designs are discussed later.

Metal O-Ring	~ 4.5" I.D.	4
Retaining Ring	5.75" Nom. Dia.	6
Long Socket HD Cap Screws	1/2" - 1-3/4"	504
Long Socket HD Cap Screws	1/2" - 1-1/4"	552
Bolts and Nuts	3/4" Dia.	192 + 384
Bolts and Nuts	7/8" dia.	12 + 24

7.1.3 Vessel Support

A possible vessel support using four equally spaced supporting saddles made of 1" carbon steel plate is shown in Figure 19.

Note: Design weight of vessel, moderator water, PT/CT assemblies, etc. is 64,000 kg.

7.2 The Supply Vessel(s)

In order to provide the necessary water inventory during the discharge period from the ruptured pressure tube, a supply vessel(s) with sufficient water inventory is required. As indicated earlier in Section 6.1, the supply vessel(s) outlet (as shown in Figure 18) may not necessarily be branched to the two feeders. In fact, separate supply vessels may be connected individually to each feeder. Such arrangements, or indeed any other suitable arrangement, are optional.

The following are the essential specifications:

Operating Pressure	11 MPa (1595.4 psia)	
Operating Temperature	300°C (572°F)	
Maximum Discharge Rate During Pressure Tube Rupture	200 kg/s	Discharge Through Both Feeders
Pressure - Time History (During Discharge Period)	Controllable	Figure 5 shows a Reference Example* of a Pressure - Time History
Discharge Period	Two Options 60 s and 120 s	
Required Water Inventory	17.5 m^3 (60 s) 33.5 m^3 (120 s)	

* Section 3.2 contains other details.

7.3 The Burst Channel

Only one burst channel is required. The design must allow its location at any of the 21 channel penetrations in the Test Calandria Vessel.

The following are the essential specifications:

7.3.1 Fuel

7.3.1.1 Bundle Assembly

Quantity Per Channel	12	
Length of Bundle	495 mm	
Outside Diameter	102.4 mm	
Configuration	37 Element	

7.3.1.2 Element Assembly

Material	Zircaloy-4	
Weight	2.319 kg	
Outside Diameter	13.08 mm	
Cladding Thickness	0.38 mm	

7.3.1.3 Pellets

Form	Cylindrical Pellets	
Material	UO_2, Tungsten, or any other Equivalent Material	Optional Depending on Laboratory Facilities
Outside Diameter	12.16 mm	
Quantity (approx.)	30	in each element
Length	16 mm	

7.3.1.4 Bundle Weight

The total weight of each bundle is 23.5 kg.

7.3.2 Pressure Tube

Material	Zirconium-2.5% wt Niobium	
Length Trimmed for Installation	6.30 m	
Inside Diameter (minimum)	103.38 mm	
Wall Thickness (approx.)	4.19 mm	
Defect	Axially Milled Defect	Orientation and Length may vary Depending on Test Conditions
Operating Pressure (max.)	11 MPa	
Operating Temperature (max.)	300°C	

7.3.3 Calandria Tube

Material	Zircaloy-2	
Inside Diameter	129.0 mm	
Wall Thickness	1.37 mm	
Length	6045.2 mm	
Defect	Axially Milled Defect(s)	Orientation and Length may vary Depending on Test Conditions
Operating Pressure	2 MPa (max.)	
Operating Temperature	110°C (max.)	

7.3.4 Garter Springs

Four typical CANDU garter springs are required. The springs are to be located the same way as in a typical CANDU reactor. The garter spring coil diameter is 5.588 mm (0.220").

7.3.5 End Fitting/Liner Tube/Shield Plug

Quantity	2 of each	Figure 3 shows the End Fitting Assembly.
Configuration	Identical to those in a typical CANDU reactor	An alternative design may be used, provided it is shown to be a representative simulation.

7.3.6 Channel/Vessel Assembly

Figure 20 shows an example of a conceptual design. The detailed design is optional.

7.3.7 Structural End Fitting Support

An external structure is required to support the end fittings in a manner representative of a typical CANDU reactor end shield. The support must also prevent the ejection of the end fittings in the case of a guillotine rupture of the burst channel.

7.3.8 Burst Initiation Method

The method of initiating a burst has been discussed in detail in Section 5.3.

7.4 The Target Channels

As indicated in Section 3.1, up to two target channels may exist during each test. During pre-test warm-up, these channels will be pressurized with hot water at the BPT operating conditions, but with minimal circulation. The following are the main specifications:

7.4.1 Fuel

7.4.1.1 Bundle Assembly

Quantity Per Channel	12
Length of Bundle	495 mm
Outside Diameter	102.4 mm
Configuration	37 Element

7.4.1.2 Element Assembly

Material	Zircaloy-4	
Weight	2.319 kg	
Outside Diameter	13.08 mm	
Cladding Thickness	0.38 mm	

7.4.1.3 Pellets

Form	Cylindrical Pellets	
Material	UO_2, Tungsten, or any other Equivalent Material	Optional Depending on Laboratory Facilities
Outside Diameter	12.16 mm	
Quantity (approx.)	30	In each element
Length	16 mm	

7.4.1.4 Bundle Weight

The total weight of each bundle is 23.5 kg.

7.4.2 Pressure Tube

Material	Zirconium-2.5% wt Niobium
Length Trimmed for Installation	6.30 m
Inside Diameter (minimum)	103.38 mm
Wall Thickness (approx.)	4.19 mm
Operating Pressure (max.)	11 MPa
Operating Temperature (max.)	300°C

7.4.3 Calandria Tube

Material	Zircaloy-2
Inside Diameter	129.0 mm
Wall Thickness	1.37 mm
Length	6045.2 mm
Operating Pressure	0.1 MPa
Operating Temperature	110°C

7.4.4 Garter Springs

Four typical CANDU garter springs are required. The springs are to be located the same way as in a typical CANDU reactor. The garter spring coil diameter is 5.588 mm (0.220").

7.4.5 Channel/Vessel Assembly

Figure 21 shows one possible design for the special end fittings, and the channel/vessel assembly. Such a design is optional, but all 21 channels must be interchangeable.

7.5 The Dummy Channels

Each of these 18 channels will have a real calandria tube, a simulated mild steel pressure tube and simulated fuel. These channels will neither be hot nor pressurized, and will be open from both ends. The specifications are given below.

7.5.1 Fuel

The fuel will be simulated. It will be made of 12 identical mild steel solid cylinders having a total mass equal to the mass of real fuel bundles plus the mass of channel water inventory plus the mass difference between the real and the simulated pressure tube. The following are the specifications:

Form	Solid Cylinders	
Material	Mild Steel	
Quantity per Channel	12	
Length of Each Cylinder	495 mm	
Diameter	93.78	
Bearing Pads	Yes	Number of Bearing Pads, shape and bearing surface dia. to pressure tube ID clearance to be prototypical.

7.5.2 Pressure Tube

Simulated mild steel pressure tubes will be used. Based on the analysis presented in Section 4.3, the following are the specifications:

Material	Mild Steel
Inside Diameter	107.94 mm
Wall Thickness	1.92 mm
Length Trimmed for Installation	6.30 m

7.5.3 Calandria Tube

Material	Zircaloy-2
Inside Diameter	129.0 mm
Wall Thickness	1.37 mm
Length	6045.2 mm
Operating Pressure	0.1 MPa
Operating Temperature	110°C (max.)

7.5.4 Garter Springs

Four typical CANDU garter springs are required. The springs are to be located the same way as in a typical CANDU reactor. The garter spring coil diameter is 5.588 mm (0.220").

7.5.5 Channel/Vessel Assembly

Figure 22 shows a conceptual design for the installation of the channels. Other suitable designs may be used, but interchangeability of all 21 channels must be preserved.

7.6 The Calandria Vessel Relief Pipes

Four relief pipes will be connected to the vessel via the provided penetrations. These pipes will be identical to those in a typical CANDU reactor. The specifications for each pipe are as follows:

Material	Carbon Steel
Diameter	18" STD.

Vertical Level from the top of the Calandria Vessel to Rupture Discs	6.0 m
Geometry	Identical to a typical CANDU reactor. Approximate dimensions are: 0.6 m pipe followed by 90° elbow followed by 45° elbow followed by 2.68 m pipe followed by 90° elbow followed by 4.26 m pipe
Rupture Disc Rating	137.8 kPa ± 5%
Rupture Disc Location	Discharge end of piping.
Normal Operating Conditions	Water level in relief pipe (approx.) 0.6 m, from top of calandria vessel, and cover gas (helium) at 27.6 kPa gauge (4 psig).

7.7 Shut-off-rod Guide Tubes (SORGTs)

Based on the scaling scheme suggested in Section 4.2, the following are the specifications of the scaled shut-off-rod guide tubes.

7.7.1 General

Quantity	11	Plus provision for 22 more to replace those damaged during testing
Material	Zircaloy-2	
Outside Diameter	127.6 mm	
Wall Thickness	1.55 mm	
Length	2.9 m	
Diameter of Holes	21.72 mm	
Longitudinal Pitch	55.02	
Pitch Along the Tube Periphery	32.97 mm	
Longitudinal Length with no holes at each end	101.5 mm	

7.7.2 In-vessel Assembly

Figure 23 shows a conceptual design for the SORGT in-vessel assembly. The locations of all the test rods are shown in Figure 19. Based on the analysis presented in Section 4.2, both ends of the SORGT will be supported in the vessel via cantilever rods (the dimensions of each rod are 10.1 mm diameter and 175 mm long to the support point). A retaining ring will be installed on the bottom cantilever, and a suitable coil spring will be placed on the top cantilever as shown in Figure 23, to maintain the SORGT's position. One of the 11 SORGTs may have stiffer supports [10] (larger diameter cantilevers) at both ends (as indicated in Figure 19).

7.8 Adjuster Rod Assembly

Provision for one rod assembly simulating an adjuster rod assembly in a typical CANDU reactor is to be made. The assembly consists of two concentric rods. The location of this rod assembly is shown in Figure 19. The following are the specifications:

7.8.1 Outer Rod

Quantity	1
Form	Perforated Tube
Material	Zircaloy-2
Outside Diameter	88.9 mm
Wall Thickness	1.55 mm
Length	2.90 m
Diameter of Holes (approx.)	22 mm
Longitudinal Pitch (approx.)	55 mm
Pitch Along the Tube Periphery (approx.)	33 mm
Longitudinal Length with no holes at each end (approx.)	102 mm

7.8.2 Inner Rod

Quantity	1
Form	Tube
Material	Stainless Steel

Outside Diameter	76.2 mm
Wall Thickness (approx.)	3.14 mm

The method of mounting this rod assembly in the vessel is similar to that described in Section 7.7.2 (see also Figure 23).

7.9 Inlet and Outlet Feeder Specifications

The burst channel inlet and outlet feeders should either be geometrically identical to the inlet and outlet feeders connected to a high power channel in a typical CANDU reactor, or of different geometry, but having the same hydraulic resistance.

Each feeder will require a venturi meter for flow measurement up to 120 kg/s.

7.10 Moderator Cooling Water System

The following are the specifications for the major components in the moderator cooling system (see Figure 18).

7.10.1 Cooling Water Tank

Operating Pressure	Open Tank	
Size (approx.)	80 m^3	
Water Temperature (nominal)	20°C	See Section 6.4, para. 3, and Figure 14

7.10.2 Circulating Pump

Rated Volumetric Flow	0.665 m^3/s	(10610 USgpm)
Rated Head	53.4 m	(175 ft.)
Driver Power (approx.)	634 kW	(850 HP)

Note that the pump head-flow characteristics should be relatively flat in the flow range of 6500 USgpm to 10600 USgpm.

During testing valve V-7 (Figure 18) must be automatically controlled to provide the necessary cooling water flow rate as shown in Figure 14, corrected for the actual temperature.

7.10.3 Standpipe

Material	Carbon Steel	
Nom. Dia.	24" STD.	
Required Water Level Above the top of the Calandria Vessel	6.0 m	Same level as that of the rupture discs on the relief pipes

7.10.4 Other Components

Pneumatic Valves	3	1 - 18"-150# Gate Valve 1 - 24"-150# Gate Valve 1 - 18"-150# Globe Valve
Venturimeter	1 (18" Dia.)	
Orifice Meter	1 (24" Dia.)	
Inter-connecting Piping	24" STD.	Length will depend on the test facility.

7.11 Catch Tank

A catch tank is required to collect the water discharging from the relief pipes and from the standpipe. The following are the necessary specifications:

Operating Pressure	Open Tank
Size (approx.)	100 m^3

7.12 Insulation

Warm-up loop, inlet and outlet feeders, supply vessel(s) and the BPT end fittings should be insulated with suitable pipe insulation to minimize heat losses.

8. INSTRUMENTATION

In order to fully characterize the thermohydraulic phenomena and the structural response of in-core components, proper instrumentation coverage is required in both the loop and the test section. Figure 18 displays the locations of the loop instruments. Table 1 lists the detailed specifications and required accuracies for the instruments and their signal conditioning units. Possible manufacturer's models which meet these specifications are also included.

The instruments should be mounted in a manner which will minimize interference with the hydraulic and dynamic events. The mounting should also be of sufficient strength to withstand the loadings during the event. A discussion of all the required instruments is presented below.

8.1 Thermocouples (Total of 73)

Thermocouples are needed to measure the temperature distribution inside the calandria vessel especially in the vicinity of the burst location. These thermocouples will be of importance in defining the bubble trajectory. Figures 24 through 28 display the proposed thermocouple locations in the test array assuming an upward central tube rupture. Each figure shows the distribution on one channel. For example Figure 24(a) shows on the upper left-hand corner of the figure the location of the channel in the tube array. A longitudinal section in the channel is shown, and cross-sections of the PT/CT assembly at specific axial locations are displayed (the pyramid-shape) showing the distribution of thermocouples on each cross-section.

Several thermocouples are also required in the warm-up and moderator loops in order to monitor pre-burst loop temperature distribution. The following are the details of the required thermocouples.

	Quantity
Calandria Vessel	50
Supply Vessel	3
Inlet Feeder	2
Outlet Feeder	2
Moderator Temperature (Inlet, Outlet, in Vessel)	5
Warm-up Loop	11

8.2 Absolute Pressure (Total of 10)

Absolute pressure transducers are required for loop and test section pressure measurements prior to burst initiation. In addition, the pressure in the supply vessel must be monitored throughout the test in order to regulate the pressure (through a feed-back system) to follow the specified pressure-time history. The following are the required pressure transducer locations and quantity.

	Quantity
Supply Vessel	1
Inlet Feeder	1
Outlet Feeder	1
Calandria Vessel	1
Calandria Relief Pipe (cover gas)	1
Warm-up Loop	5

8.3 Differential Pressures (Total of 11)

Differential pressure transducers are required for both flow measurements (e.g. in venturies and orifice meters) and fluid level measurements. The following are the quantities and locations of the required transducers.

	Quantity
Inlet Feeder (Venturi)	1
Outlet Feeder (Venturi)	1
Inlet and Outlet Feeders	2
Supply Vessel Level	2
Calandria Vessel Level	1
Relief Pipe Level	1
Warm-up (Venturi)	1
Cooling Water Inlet (Venturi)	1
Cooling Water Outlet (Orifice)	1

8.4 Strain Gauges (Total of 12)

Strain gauges are required to be placed near the rolled ends of the target pressure tubes. Figure 24(a) and Figure 27(b) display the locations of the required strain gauges. At least three axial strain gauges are required, to measure bending loads, equally spaced around the circumference at each end. The following is the required quantity.

	Quantity
Target Pressure Tubes	12

8.5 Accelerometers (Total of 12)

Accelerometers are required on the shut-off-rod guide tubes and the burst and target pressure tubes. The following are the required quantities:

	Quantity
Shut-off-rod Guide Tubes	9
Target Pressure Tubes (Bi-axial)	2
Burst Pressure Tube (Bi-axial)	1

8.6 Dynamic Pressures (Total of 13)

In order to track the possible shock wave and/or pressure wave in the calandria vessel, dynamic pressure transducers are required. Figure 29 displays the proposed locations for these transducers. The majority of the transducers are placed in the burst plane. The transducers placed in the other planes are intended to determine the shape of the pressure wave (spherical or cylindrical). The quantities and general locations of these transducers are indicated below.

	Quantity
Wall of Calandria Vessel	3
Inside Calandria Vessel	10

8.7 Void Probes (Total of 10)

In order to determine the bubble trajectory, it is proposed to use void probes which will be placed in the same locations as the dynamic pressure transducers (see Figure 29). The quantity and locations of the void probes are indicated below.

	Quantity
Inside Calandria Vessel (same location as the dynamic pressure transducers)	10

8.8 Flow Measurements (Total of 5)

The following are the required flow measurements. These measurements will, of course, be inferred from the differential pressure measurements mentioned in Section 8.3.

	Quantity
Inlet Feeder (Venturi)	1
Outlet Feeder (Venturi)	1
Supply Vessel (Level)	1
Moderator Inlet (Venturi)	1
Moderator Outlet (Orifice)	1

8.9 Crack Propagation Gauges (Total of 4)

Sets of trip-wires will be placed on each side of the defects on both the burst calandria tube and pressure tube to measure crack propagation velocity as indicated below.

	Quantity
Burst Pressure Tube	2
Burst Calandria Tube	2

8.10 High Speed Video Cameras (Total of 2)

High speed video cameras are required to record the post-test events. The following are the required locations and quantity.

	Quantity
Side and end of Calandria Vessel	2

8.11 Lighting Sets (Total of 4)

	Quantity
Lighting Sets for use with the high speed video cameras	4

8.12 Permanent Displacement Gauges (Total of 6)

Simple telescopic antenna-type gauges which will measure the minimum distance, experienced during testing, between two adjacent PT/CT assemblies at any desired location are required. The locations of these devices are given below.

	Quantity
Burst Channels	2
Target Channels	4

9. DATA ACQUISITION SYSTEM

All measurements should be computer acquired and stored for later analysis. Up to 106 channels at a sampling rate of 5 Hz, and up to 41 channels at a sampling rate of 1 kHz are required. The latter sampling rate is only required for a period of 15 s from burst initiation, after which the sampling rate shall be 5 Hz. The data acquisition system should be checked systematically before starting testing to provide assurance that all elements of the measurement system are operating correctly and accurately. For the high frequency response instrumentation, e.g., the dynamic pressure transducers, the accelerometers, etc., an FM analog tape recorder (capable of speeds up to 120 ips) may be used instead of the 1 kHz scanner (41 channels). The recorded signals will be played back at a lower speed, after testing, into the digital system and recorded for later analysis.

10. EXPERIMENTAL

The primary objective of the test program is to investigate i) the thermo-hydraulic phenomena associated with a postulated pressure tube/calandria tube rupture and, ii) the resulting loadings on the shut-off-rod guide tubes and other pressure tube/calandria tube assemblies. The phenomena expected to take place include a) shock waves, b) transient bulk pressurization, c) jet discharge (flashing, periodical bubble expansion and collapse, and d) other possible damaging mechanisms which may be identified (e.g. vibration, etc.).

Prior to testing, bench testing of at least two pressure tubes to demonstrate that the specified burst pressure can be achieved with a tolerance of $\pm$ 1 MPa, must be conducted.

A comprehensive test matrix with a progressive test plan is proposed. The test variables considered are i) the number of PT/CT assemblies in the test array, ii) burst tube location in the array, iii) primary coolant temperature, iv) pressure tube defect orientation, v) pressure tube defect w.r.t. calandria tube defect, vi) calandria tube thickness, vii) shut-off-rod guide tube arrangement, and viii) pressure tube inventory (fuel/no fuel). The test matrix has a total of 11 tests designed to meet the objectives of the program. This test matrix is shown in Table 2. Tests 1, 2 and 3 are listed in physical order of testing. The shown order of the remaining tests is not a necessity.

Upon the completion of each test, a visual inspection and photographic record where possible, of all in-core components, e.g., shut-off-rod guide tubes, all PT/CT assemblies, etc., shall be carried out, and all anomalies shall be photographically recorded in detail.

It should be noted that in each test except the first*, up to two target channels may have to be relocated. Since the pressure tubes of these channels have rolled end joints, these channels may have to be cut out and replaced. In addition, allowance should be made for replacing up to 15 thermocouples, 12 strain gauges, 2 dynamic pressure transducers, 10 void probes, 4 accelerometers and 4 crack propagation gauges.

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* The first test has only one channel (see Table 2).

11. LABORATORY SURVEY, COST ESTIMATE AND SCHEDULE

A document containing the proposed facility specifications and test program has been sent to firms in Canada which expressed interest in the program.

The firms were asked to present i) a technical proposal stating how they intend to meet the system performance specifications, ii) a facility description, detailing where the work is to be performed, what existing staff and equipment are available for conducting this work and what modifications will be required to accommodate the work, iii) a detailed cost estimate based on the submitted document, and iv) a schedule for completing the work from the time of receipt of order.

Meetings were arranged with staff from the firms which have requested so. All but one of the candidate facilities were visited and inspected.

The survey indicated that several Canadian laboratories can conduct the proposed program. The current estimated cost for the design and construction of the facility, conducting the test program and reporting is between $4,000,000 and $5,000,000. The full program would require 3 to 4 years to complete. The details of this investigation are presented elsewhere [27].

12. CONCLUSIONS

A study has been prepared on the feasibility of conducting pressure tube/calandria tube rupture tests in a closed tank. The tank is a full length model of a typical CANDU calandria vessel, scaled down in diameter. The tank is to house up to 21 full-size pressure tube/calandria tube assemblies (5 x 5 square array with no corner channels), 11 scaled shut-off-rod guide tubes, and one scaled adjuster rod assembly.

The study includes the following:

(a) a review of background information.

(b) an analytical investigation on the scaling problem of the calandria vessel, the shut-off-rod guide tubes and the dummy pressure tube/calandria tube assemblies. The scaling schemes, design features and fluid conditions were chosen such that they allow for the generation of all representative pressure and temperature transients, the characterization in full detail of the thermohydraulic phenomena and associated structural loadings and responses, and the inspection of all in-core components following each test.

(c) definition of a pressure tube/calandria tube burst initiation method. The method has been used successfully before and does not add energy to the system.

(d) a complete list of facility specifications including, the test loop, test procedure, test calandria vessel, the burst channel, the target channels, the dummy channels, the water inventory supply vessel, the relief pipes, the shut-off-rod guide tubes, the adjuster rod assembly, the moderator cooling water system, the catch tank, and the required thermal insulation. General arrangement drawings for all relevant components have been prepared as well.

(e) the required instrumentation coverage to fully characterize the thermohydraulic phenomena and the resulting structural responses of all relevant in-core components.

(f) the requirements of the data acquisition system.

(g) a proposed test matrix with a progressive test plan which would avoid damaging the tube array prematurely.

(h) a survey and evaluation of existing facilities which could provide the required high pressure, temperature and fluid inventory, and support staff.

(i) a detailed cost estimate and schedules for the design and construction of the facility, instrumentation, conducting the test program and reporting.

The study confirms that the program is technically and practically feasible. Several Canadian laboratories have the capability to conduct this study. The current estimated cost for the design and construction of the facility, conducting the test program and reporting is between $4,000,000 and $5,000,000. The full program would require 3 to 4 years to complete.

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TABLE 1 - INSTRUMENTATION

MEASUREMENT	TRANSDUCER	SIGNAL CONDITIONING	
		REFERENCE JUNCTION	AMPLIFIER
TEMPERATURE (CALANDRIA)	CLAUD S. GORDON**	CONSOLIDATED OHMIC MODEL VJR 692	ECTRON MODEL 687
THERMOCOUPLE (50*)	Junction: Type K (GND) Description: 1.3 mm Solid Wire Insulation: Fiberglass Accuracy : ± 0.75%	Temp.: 65.5°C Acc.: ± 0.11°C Stab: ± 0.05°C Noise: < 2μV	F.R.: DC to 100 Hz Noise: 2.5 μV RTI Lin.: ± 0.01% Full Isolation
		REFERENCE JUNCTION	AMPLIFIER
TEMPERATURE (FEEDERS, SUPPLY VESSEL, ETC.)	CLAUD S. GORDON	CONSOLIDATED OHMIC MODEL VJR 692	ECTRON MODEL 687
THERMOCOUPLES (23)	Junction: Type K (UNGND) Sheath Dia: 3 mm S'STL Accuracy: ± 0.75% Time Constant: 2 s	Temp.: 65.5°C Acc.: ± 0.11°C Stab.: ± 0.05°C Noise: < 2μV	F.R.: DC to 100 Hz Noise: 2.5 μV RTI Lin.: ± 0.01% Full Isolation
ABSOLUTE PRESSURE (FEEDERS, SUPPLY VESSEL, ETC.)	ROSEMOUNT INSTRUMENTS MODEL 1151GP9E12BIC6		
CAPACITANCE TYPE TRANSMITTER (10)	Accuracy: ± 0.25% Stability: 0.25% Temp. Effect: ± 0.5% F.S/40°C P/S Effect: < 0.005% span/volt	Line Regulation: 0.05% Load Regulation: 0.1% Noise: < 1 mV RMS Temp. Coeff.: - < 0.2%/°C	

* Indicates the total number required.

** These are suggested manufacturer's models. Other models which meet the required specifications can be used.

TABLE 1 - INSTRUMENTATION

MEASUREMENT	TRANSDUCER	SIGNAL CONDITIONING
DIFFERENTIAL PRESSURE (LEVEL, FLOW MEASUREMENTS FEEDERS, ETC.) CAPACITANCE TYPE TRANSMITTERS (8)	ROSEMOUNT INSTRUMENTS MODEL 1151DPG12BIC6	
	Accuracy: ± 0.2% Linearity: ± 0.1% Stability: ± 0.2% Temp. Effect: ± 0.5% F.S./40°C	Line Regulation: 0.05% Load Regulation: 0.1% Noise: < 1 mV RMS Temp. Coeff.: < 0.2%/°C
FLOW MEASUREMENT (FEEDERS AND WARM-UP LOOP) STRAIN GAUGE PRESSURE TRANS-DUCER(3)	VIATRAN MODEL 120	EXCITATION/ BALANCING AMPLIFIER ECTRON MODEL 687
	F.R.: DC to 20 kHz Error Band: ± 0.5% F.S. Temp. Range: -54 to 120°C Response Time: < 1 ms	Exc.: 10 VDC Bal.: Yes F.R.: DC to 100 Hz Noise: 2.5 µV RTI Lin.: ± 0.01% Full Isolation
STRAIN (TARGET PT) WELDABLE STRAIN GAUGE (12)	EATON/AILTECH MODEL SG125	VISHAY MODEL 2120
	Range: ± 20,000 µ in/in Fatigue: < 10E6 cycles Gauge: Quarter Bridge/120 Ohm Mat. Comp.: 3.1x10E-6 in/in/°F (24 to 315°C)	F.R.: DC - 5 kHz Noise & Drift: 10 µV R.T.I. Linearity: ± 0.05% Int. Cal.: ± 1000 µ in/in ± 1% @ G.F. = 2
ACCELERATION (SORGT) HIGH SHOCK ACCELEROMETER(9)	PCB PIEZOTRONICS MODEL 305A05 (MODIFIED)	PCB PIEZOTRONICS MODEL 483A
	Range: 2500 g (2 mV/g) Temp. Range: -70 to +120°C Rise Time: 5 µs RESONANCE: 60 kHz	Excitation: 22 VDC Gain: 1 Noise: 600 µV p-p D.C. Offset: 30 mV max.

TABLE 1 - INSTRUMENTATION

MEASUREMENT	TRANSDUCER	SIGNAL CONDITIONING
ACCELERATION (TARGET AND BPT) ACCELEROMETER* BI-AXIAL MOUNT (3)	ENDEVCO MODEL 2291 (MODIFIED)	ENDEVCO MODEL 2732 AND 2730
	Range: 2000 g Temp. Range: 180 to 400°C F.R.: 20 Hz to 20 kHz Resonance: 250 kHz	Accuracy: ± 1.5% F.S. F.R.: 2 Hz to 50 kHz (typ.) Linearity: ± 1% Stability: > 1%
DYNAMIC PRESSURE (CALANDRIA) PIEZOELECTRIC TRANSDUCER (13)	PCB PIEZOTRONICS MODEL 111M82	PCB PIEZOTRONICS MODEL 483A
	Range: 3.5 MPa Temp. Range: 70 to 135°C Rise Time: 2 µs Resonance: 400 kHz	Excitation: 22 VDC Gain: 1 Noise: 600 µV p-p D.C. Offset: 30 mV max.
VOID MEASUREMENT (CALANDRIA) CONDUCTANCE PROBE (10)	VOID PROBE	AMPLIFIER/ COMPARATOR
	Tip Size: 0.002 inch Material: S'STL Insulation: Epoxy	Input Imped.: 10E11 Ohms Noise: 4 µV R.T.I. Gain: 100 dB (typ.) Comparator: Dual Window
CRACK PROPAGATION (PT AND CT) TRIP WIRES (4 GAUGES) 4 EL. EACH)	CRACK PROPAGATION GAUGE	EXCITATION/TEST INSTRUMENT
	Type: Ungrounded Wire: 2 Conductor Sheath: S'STL Type 316 O.D.: 0.020 inch	Excitation: 18 VDC Compensation: Yes Insulation Test: Yes Continuity Test: Yes

* If available.

TABLE 1 - INSTRUMENTATION

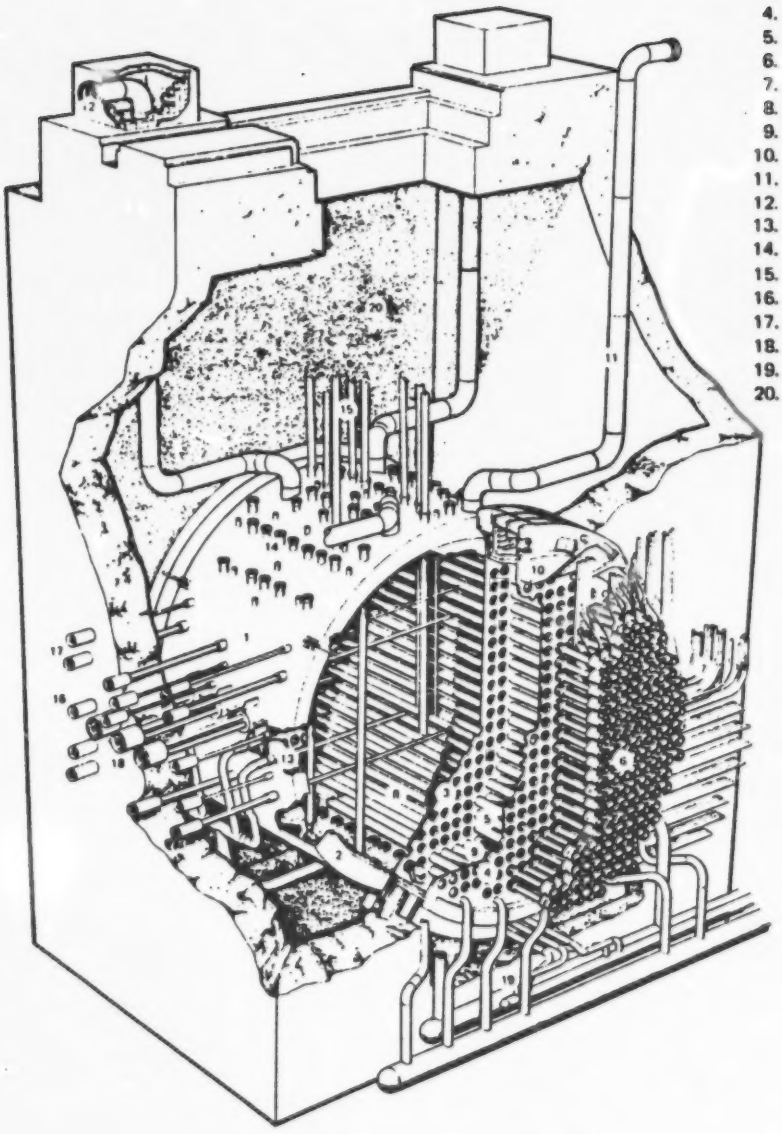
MEASUREMENT	TRANSDUCER	SIGNAL CONDITIONING
	INSTRUMENTATION MARKETING CORP. MODEL HSV-200	
GROSS MOTION HIGH SPEED VIDEO CAMERA (2)	System: N.T.S.C. Colour Speed: 200 fps	None
DISPLACEMENT (BURST AND TARGET TUBES) TELESCOPIC ANTENNA GAUGES (6)	Range: 3 inch Resolution: 0.020 inch	None

TABLE 2: PROPOSED TEST MATRIX

TEST VARIABLE	SPECIFICATIONS	TEST NUMBER										
		1	2	3	4	5	6	7	8	9	10	11
No. of Tubes in Test Array	1	x										
	9			x								
	21		x		x	x	x	x	x	x	x	x
Burst Tube Location in Array	Centre	x	x	x		x	x	x	x	x	x	x
	Outside				x							
Coolant Temperature (°C)	300					x						
	280*	x	x	x	x		x	x	x	x	x	x
Pressure Tube Defect Orientation	Top		x									
	Side	x		x	x	x	x		x	x	x	x
	Other							x				
Pressure Tube Defect W.R.T. Calandria Tube Defect	In-line	x	x	x	x	x	x	x	x	x		x
	180°										x	
	Thin Tube** (Burst Channel)											50%
SORGT Arrangement	Figure 19		x	x	x	x	x	x	x	x	x	x
	Other	None										
Pressure Tube Inventory	No Fuel									x		
	Full	x	x	x	x	x	x	x	x		x	x

* Prototypical

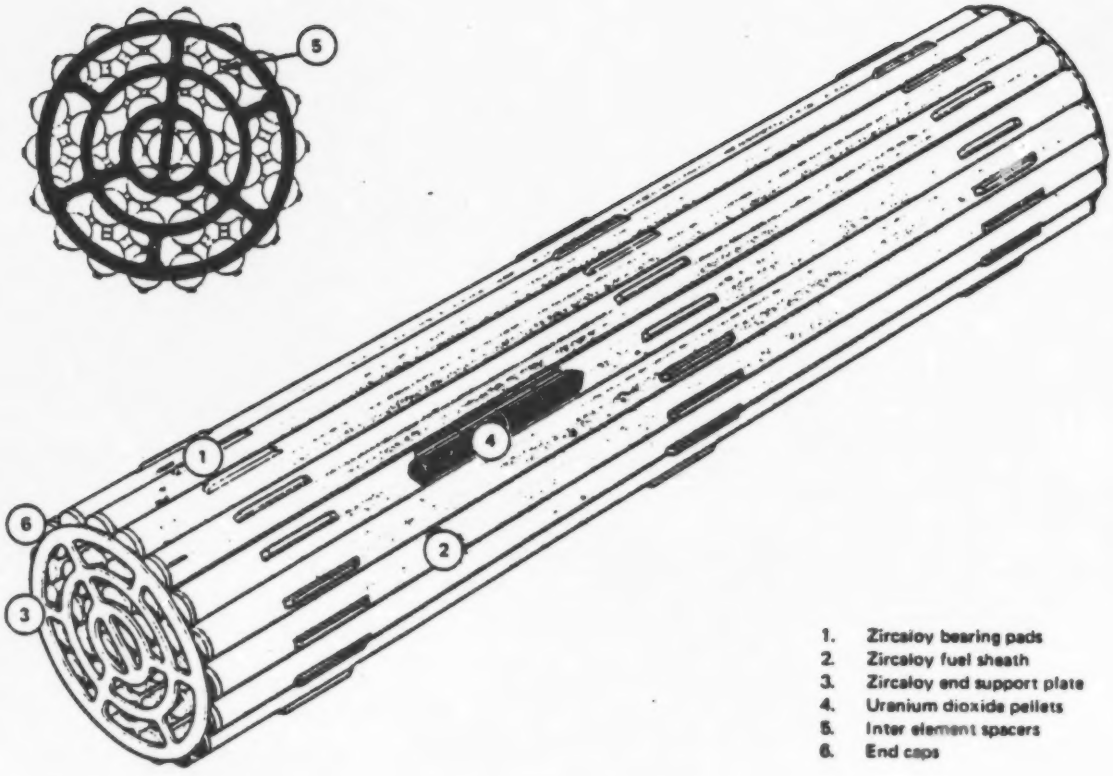
** Only Test #11 shall have a 50% thinner (w.r.t. prototypical) calandria tube. All other tests will have prototypical calandria tubes.



1. Calandria
2. Calandria shell
3. Calandria side tube sheet
4. Fuelling machine side tube sheet
5. Lattice tubes
6. End fittings
7. Feeders
8. Calandria tubes
9. Steel ball shielding
10. Annular shielding slab
11. Pressure relief pipes
12. Rupture disc
13. Moderator inlets (4 each side)
14. Reactivity control nozzles
15. Reactivity control devices
16. Horizontal flux detectors (9)
17. Poison injector nozzles (6)
18. Ion chamber cooling piping
19. End shield cooling piping
20. Calandria vault (light water shield)

FIGURE 1: Reactor Assembly

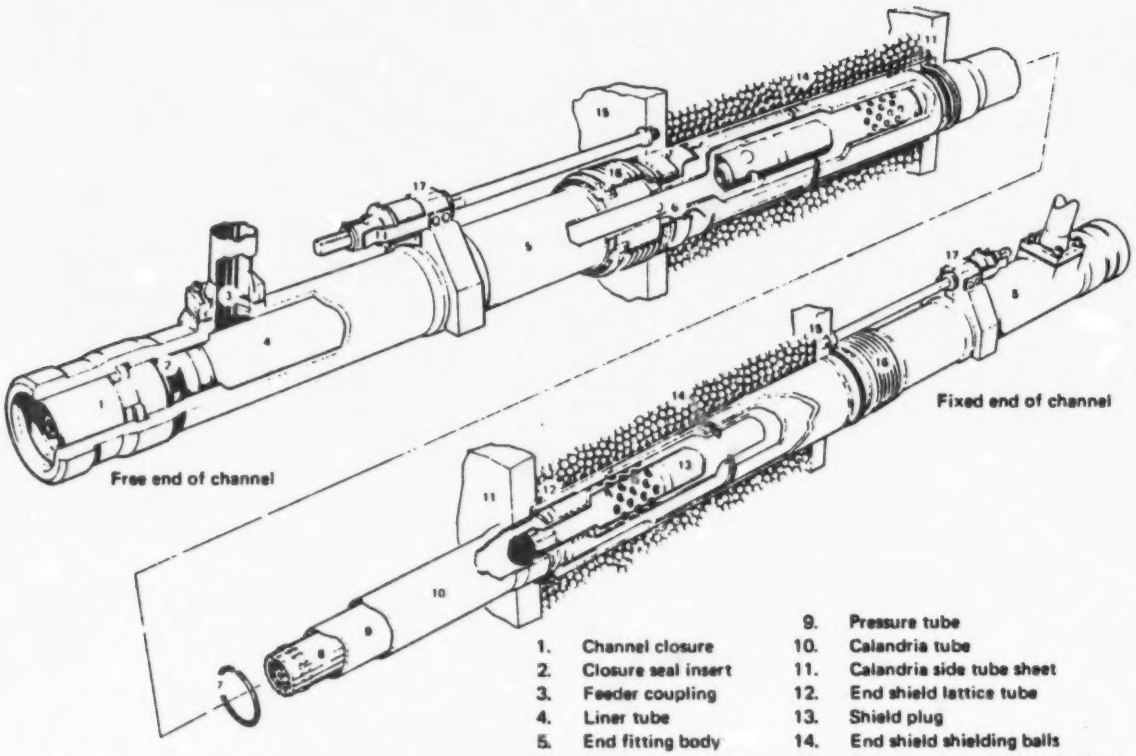
REPRODUCED WITH THE PERMISSION OF ATOMIC ENERGY OF CANADA LTD.



1. Zircaloy bearing pads
2. Zircaloy fuel sheath
3. Zircaloy end support plate
4. Uranium dioxide pellets
5. Inter element spacers
6. End caps

FIGURE 2: 37 Element Fuel Bundle

REPRODUCED WITH THE PERMISSION OF ATOMIC ENERGY OF CANADA LTD.



1. Channel closure
2. Closure seal insert
3. Feeder coupling
4. Liner tube
5. End fitting body
6. End fitting bearing
7. Tube spacer
8. Fuel bundle
9. Pressure tube
10. Calandria tube
11. Calandria side tube sheet
12. End shield lattice tube
13. Shield plug
14. End shield shielding balls
15. Fuelling machine side tube sheet
16. Channel annulus bellows
17. Channel positioning assembly

FIGURE 3: Channel Assembly Mounted in End Shield

REPRODUCED WITH THE PERMISSION OF ATOMIC ENERGY OF CANADA LTD.

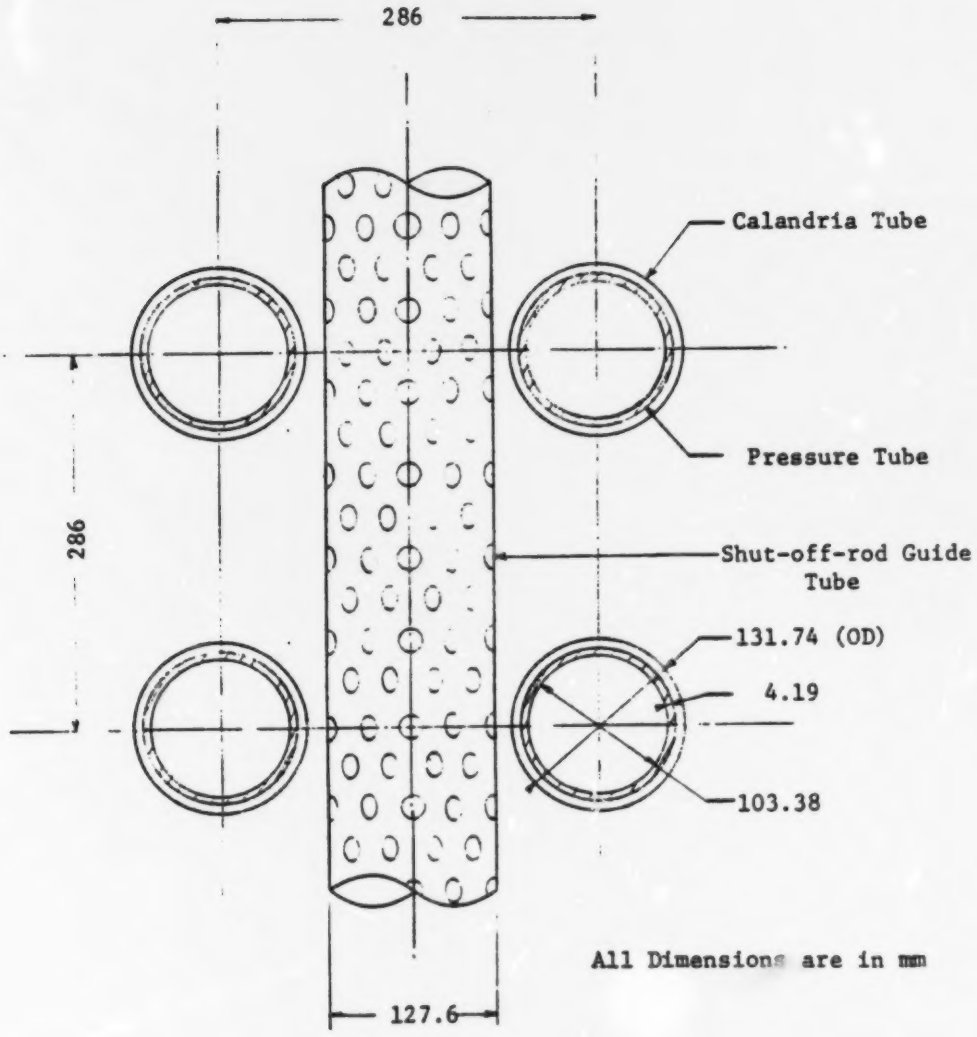


FIGURE 4: Typical CANDU Channel Lattice and Shut-Off-Rod Guide Tube

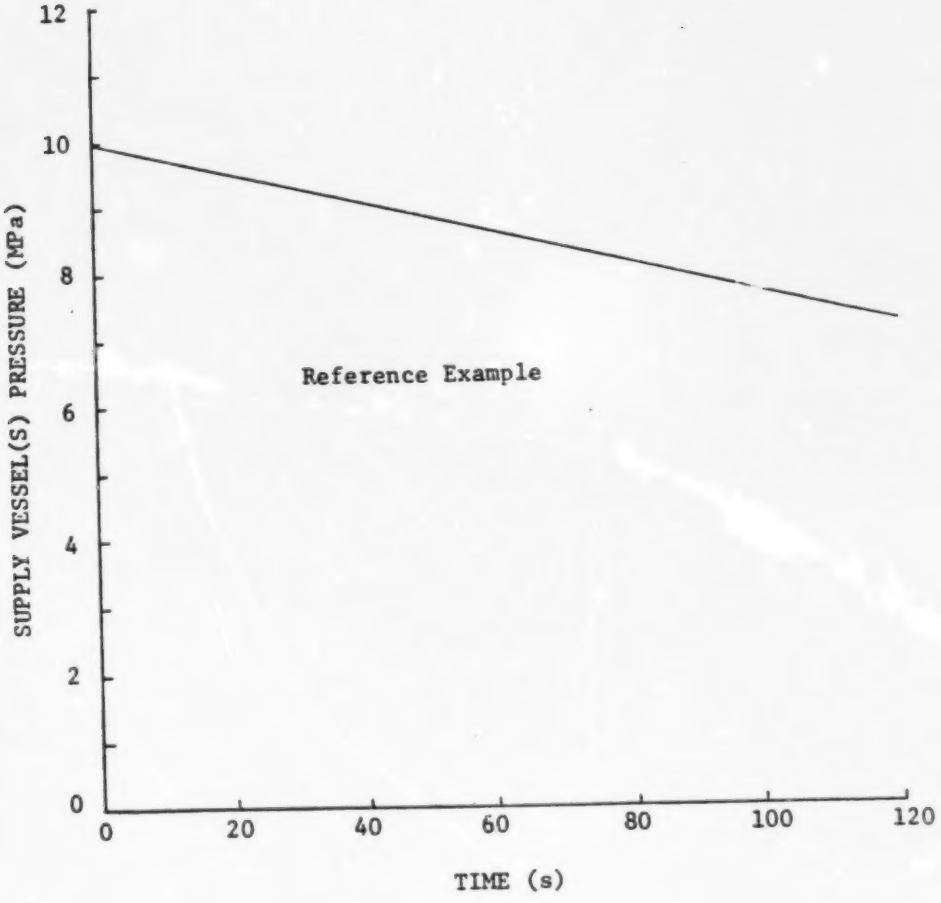


FIGURE 5: Reference Example for the Supply Vessel(s) Required Controlled Pressure-Time History

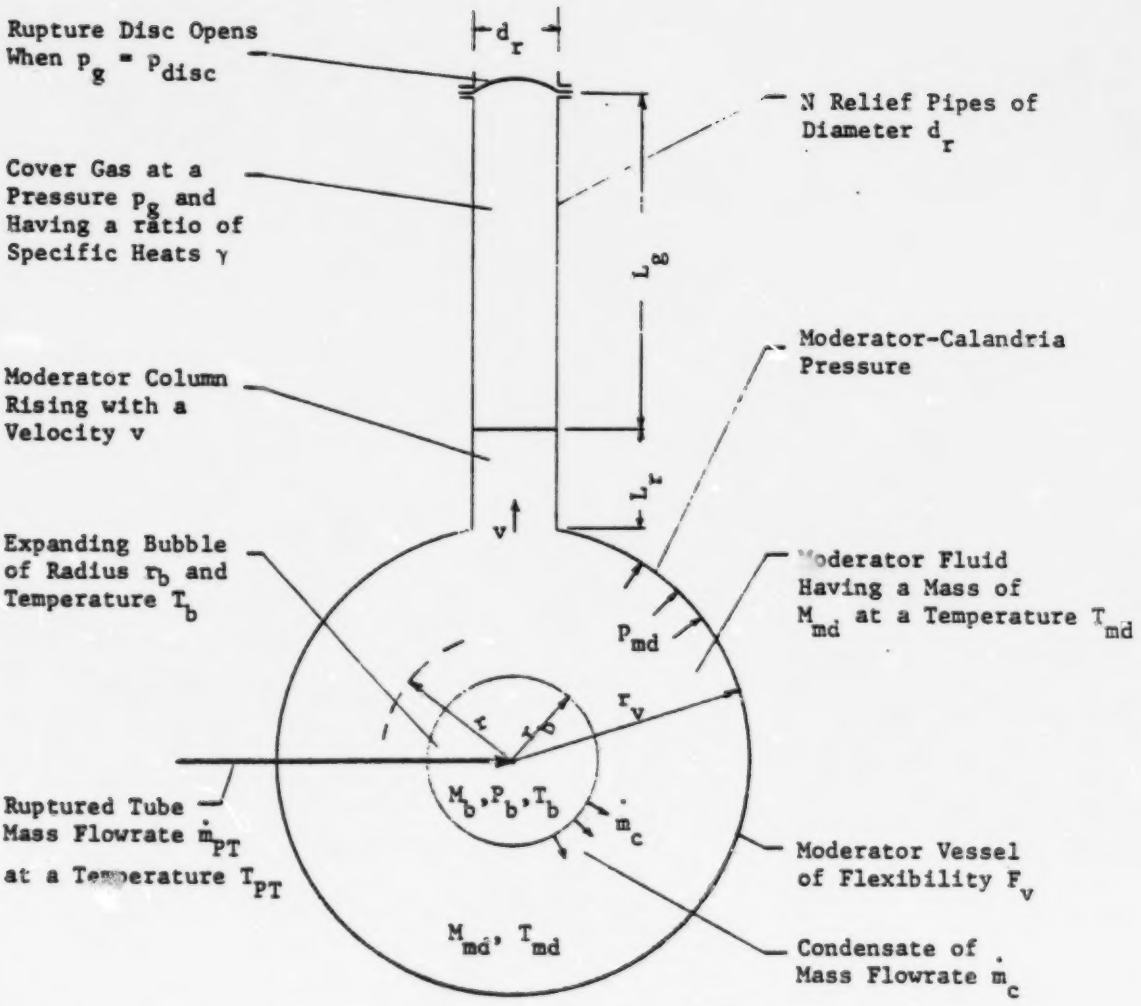

Rupture Disc Opens When $p_g = p_{disc}$
d_r
N Relief Pipes of Diameter d_r
Cover Gas at a Pressure p_g and Having a ratio of Specific Heats γ
L_∞
Moderator-Calandria Pressure
Moderator Column Rising with a Velocity v
L_r
v
Expanding Bubble of Radius r_b and Temperature T_b
Moderator Fluid Having a Mass of M_{md} at a Temperature T_{md}
p_{md}
r_v
r
r_b
M_b, P_b, T_b
$\dot{m}_c$
Ruptured Tube Mass Flowrate $\dot{m}_{PT}$ at a Temperature T_{PT}
Moderator Vessel of Flexibility F_v
M_{md}, T_{md}
Condensate of Mass Flowrate $\dot{m}_c$

FIGURE 6: Model Schematic for Transient Bulk Pressurization Analysis

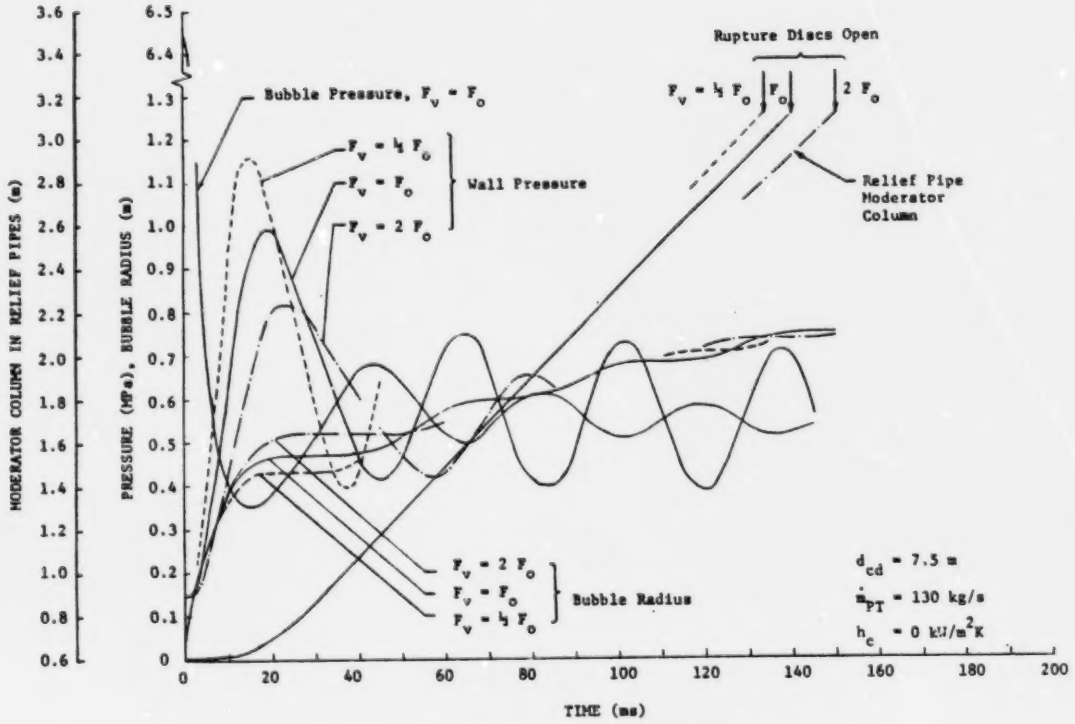


FIGURE 7: Effect of Vessel Flexibility on Transient Bulk Pressurization

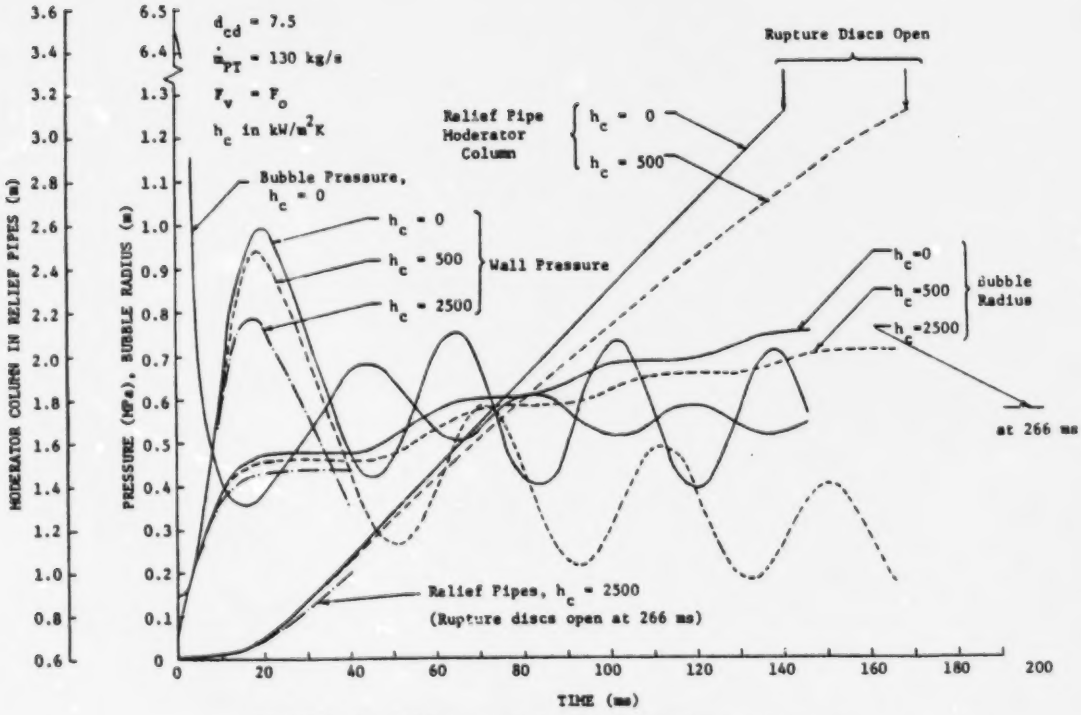


FIGURE 8: Effect of Bubble Condensation on Transient Bulk Pressurization

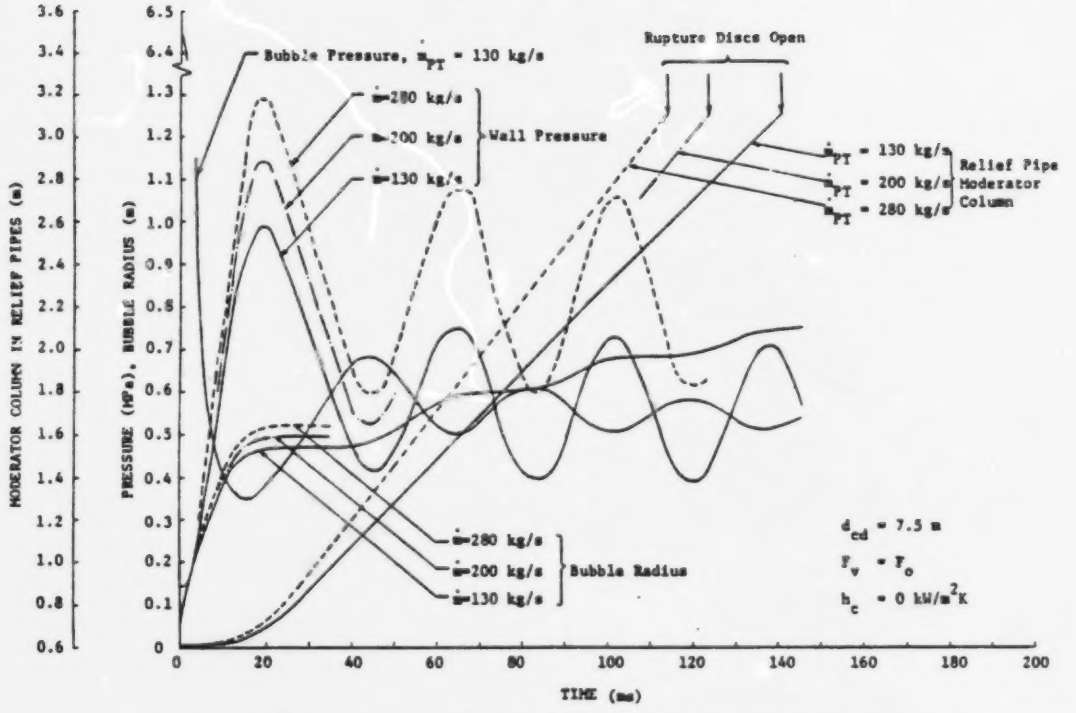


FIGURE 9: Effect of Ruptured Pressure Tube Mass Flowrate on Transient Bulk Pressurization

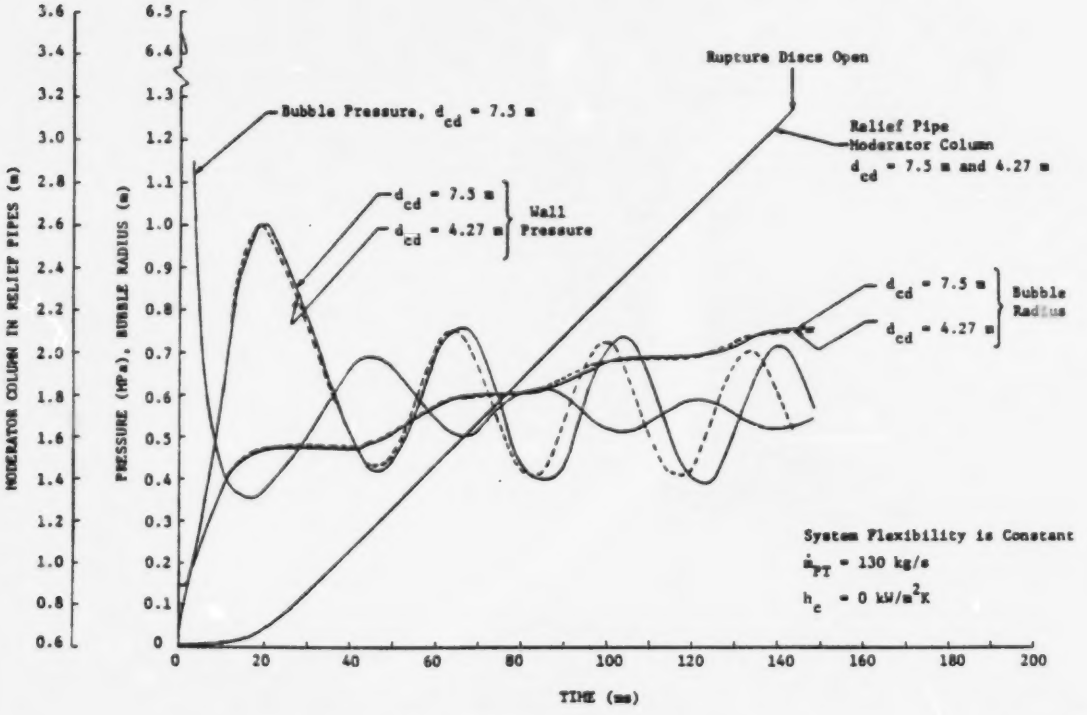

Rupture Discs Open
Bubble Pressure, d_{cd} = 7.5 m
Relief Pipe Moderator Column
d_{cd} = 7.5 m and 4.27 m
d_{cd} = 7.5 m
d_{cd} = 4.27 m
Wall Pressure
d_{cd} = 7.5 m
d_{cd} = 4.27 m
Bubble Radius
System Flexibility is Constant
$\dot{m}_{PT}$ = 130 kg/s
h_c = 0 kW/m^{2}K
MODERATOR COLUMN IN RELIEF PIPES (m)
PRESSURE (MPa), BUBBLE RADIUS (m)
TIME (ms)

FIGURE 10: Effect of Vessel Diameter on Transient Bulk Pressurization

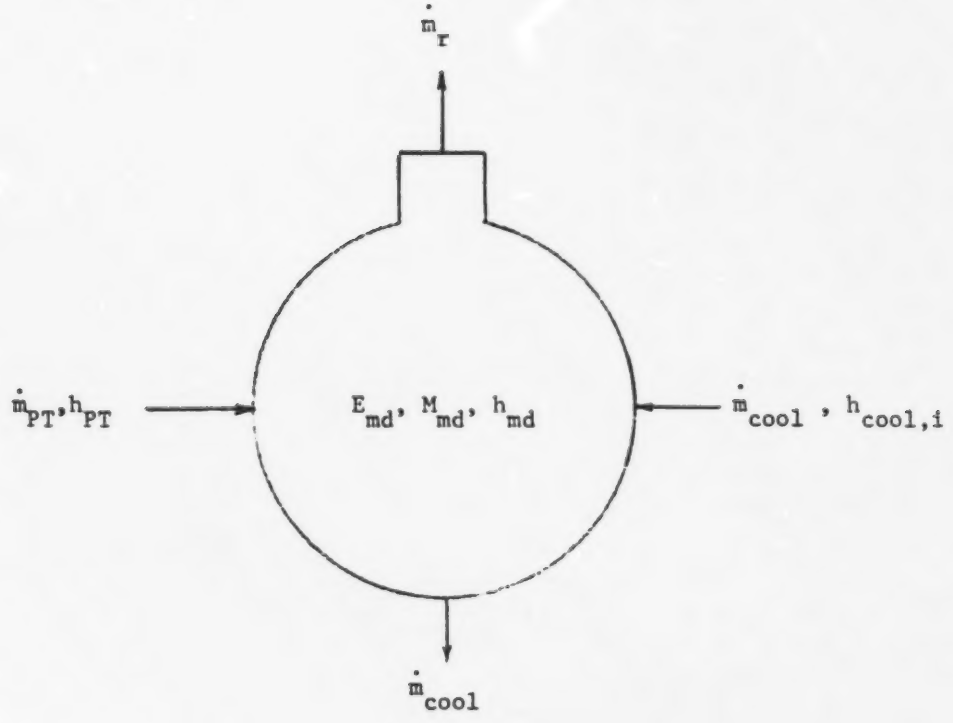


FIGURE 11: Model Schematic for Transient
Moderator Bulk Temperature Analysis

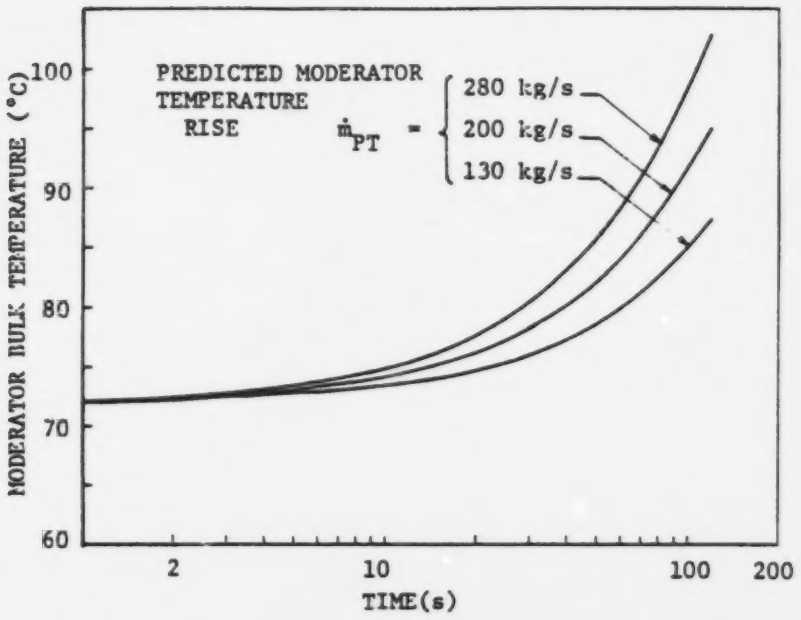


FIGURE 12: Predicted Reactor Moderator Bulk Temperature Rise for Various Discharge Mass Flowrates (T_{PT} = 280°C, P_{PT} = 10 MPa)

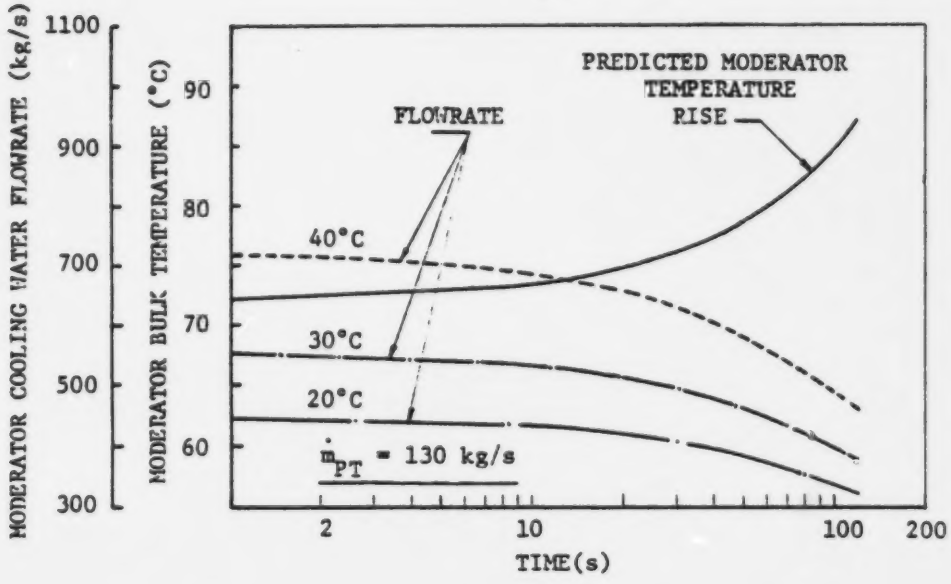


FIGURE 13: Scaled Vessel Moderator Cooling Water Mass Flowrate Requirements for $\dot{m}_{PT}$ = 130 kg/s

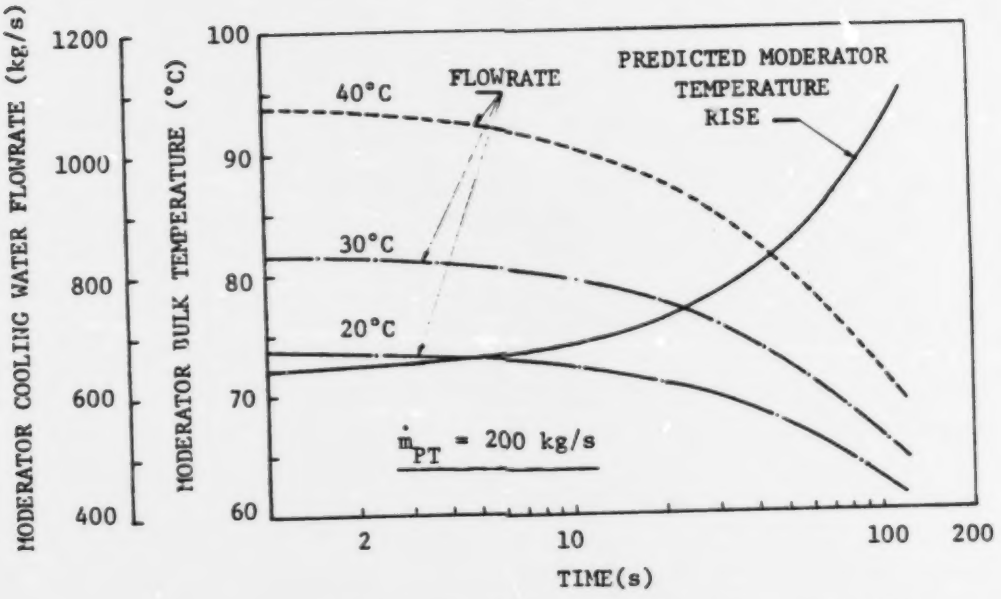


FIGURE 14: Scaled Vessel Moderator Cooling Water Mass Flowrate Requirements for $\dot{m}_{PT}$ = 200 kg/s

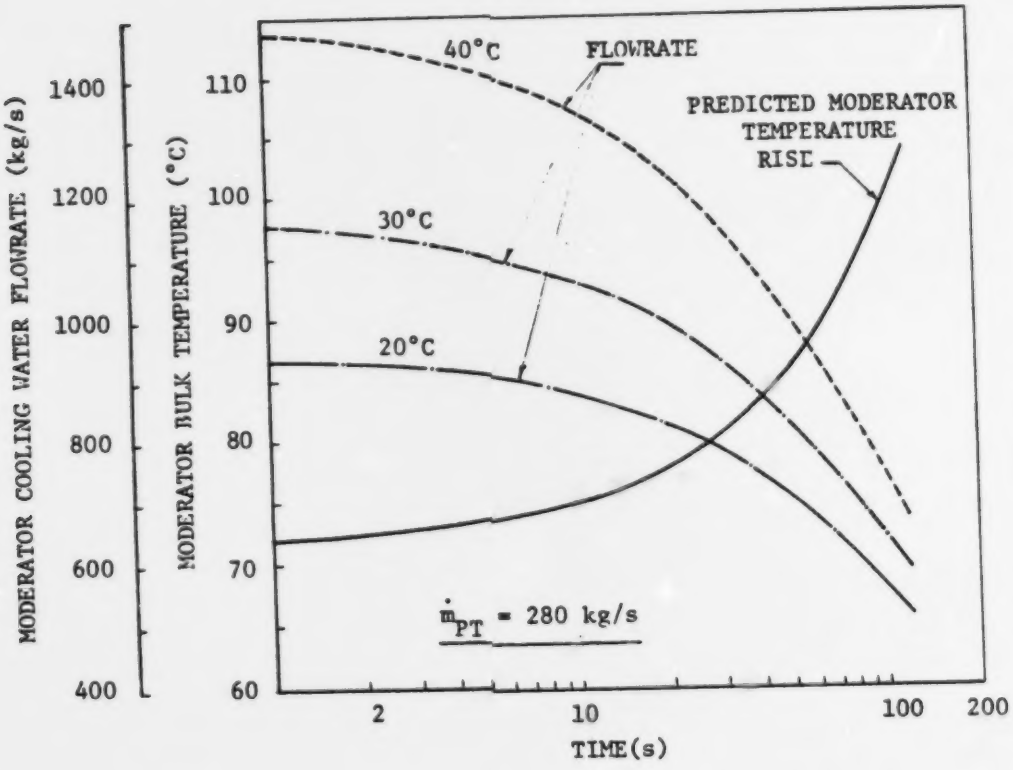


FIGURE 15: Scaled Vessel Moderator Cooling Water Mass Flowrate Requirements for $\dot{m}_{PT}$ = 280 kg/s

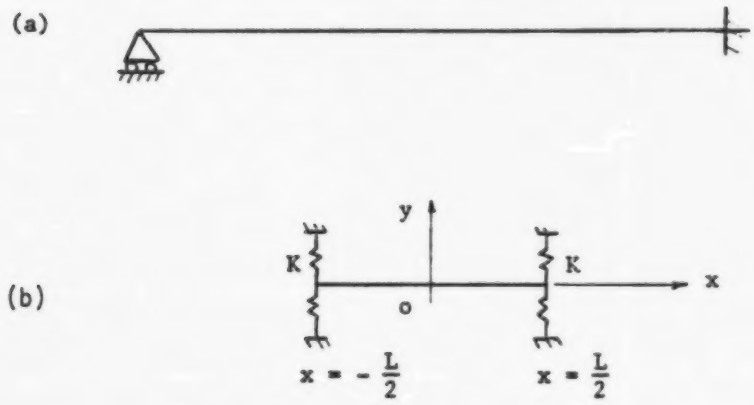


FIGURE 16: Beam Representation of the SORGT
(a) Typical CANDU SORGT
(b) Scaled SORGT

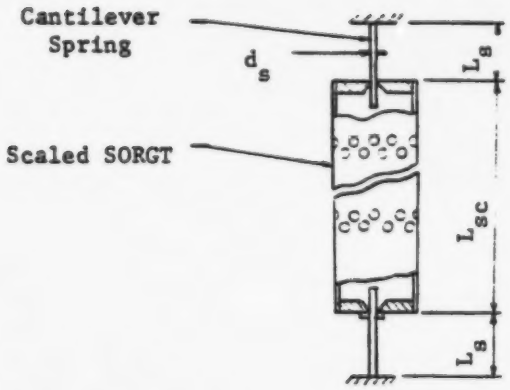
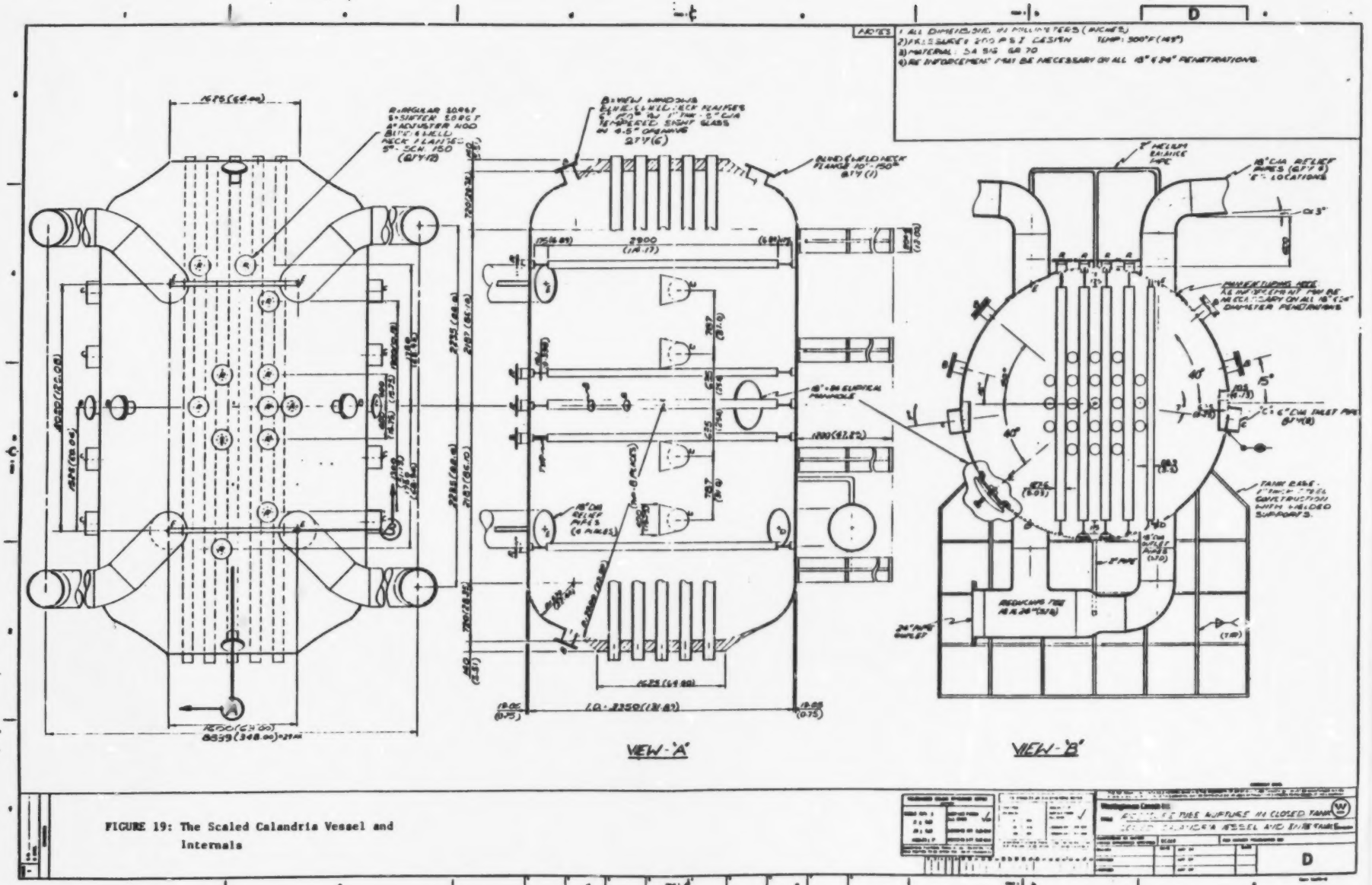


FIGURE 17: A Schematic of the Scaled SORGT Displaying the End Cantilever Springs


NOTES
1 ALL DIMENSIONS IN MILLIMETERS (INCHES)
2) PRESSURE: 200 P.S.I. CASTAN TEMP: 300°F (149°)
3) MATERIAL: SA 516 GR 70
4) RE ENFORCEMENT MAY BE NECESSARY ON ALL 18" & 24" PENETRATIONS
VIEW-'A'
VIEW-'B'
FIGURE 19: The Scaled Calandria Vessel and Internals

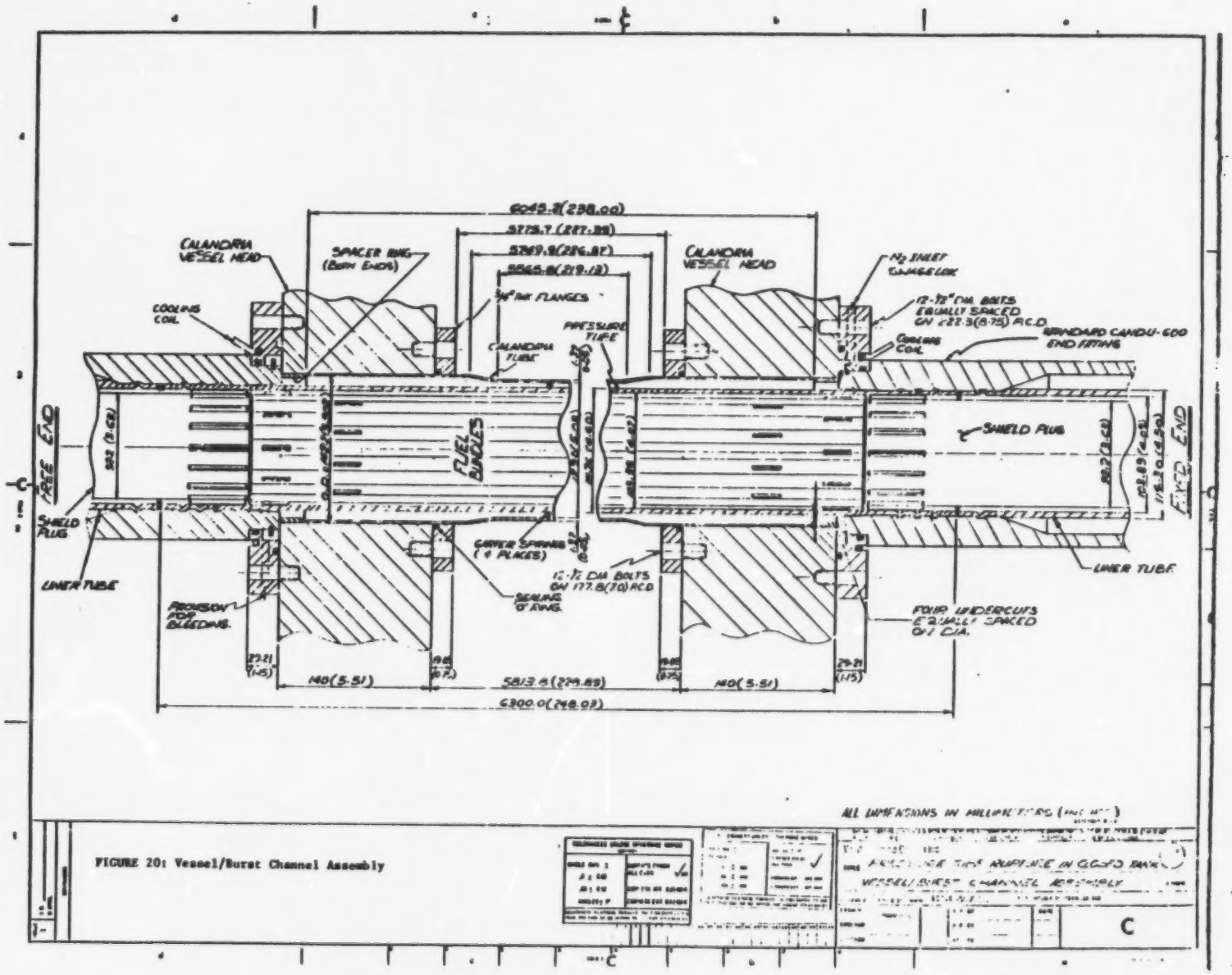


FIGURE 20: Vessel/Burst Channel Assembly

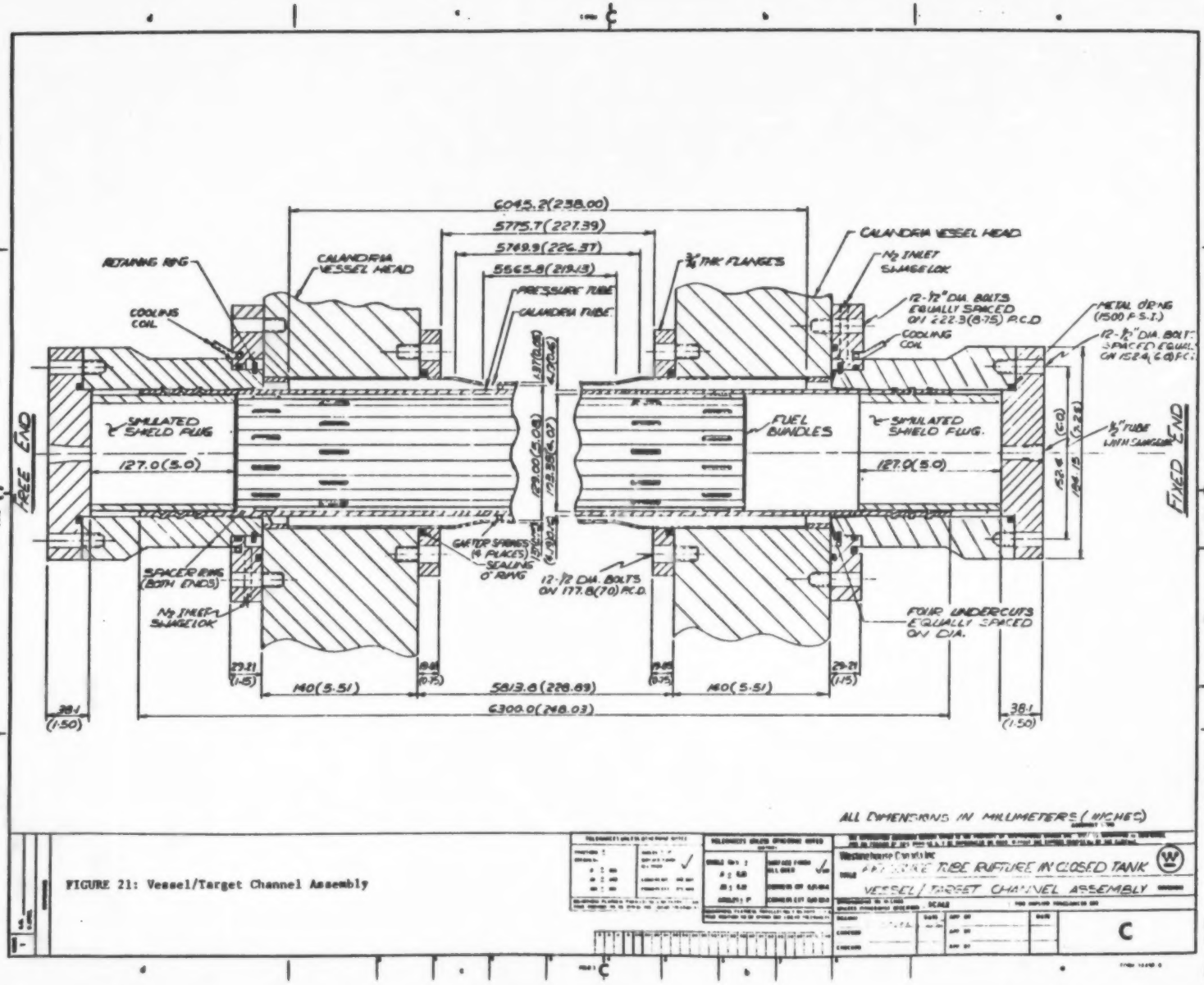
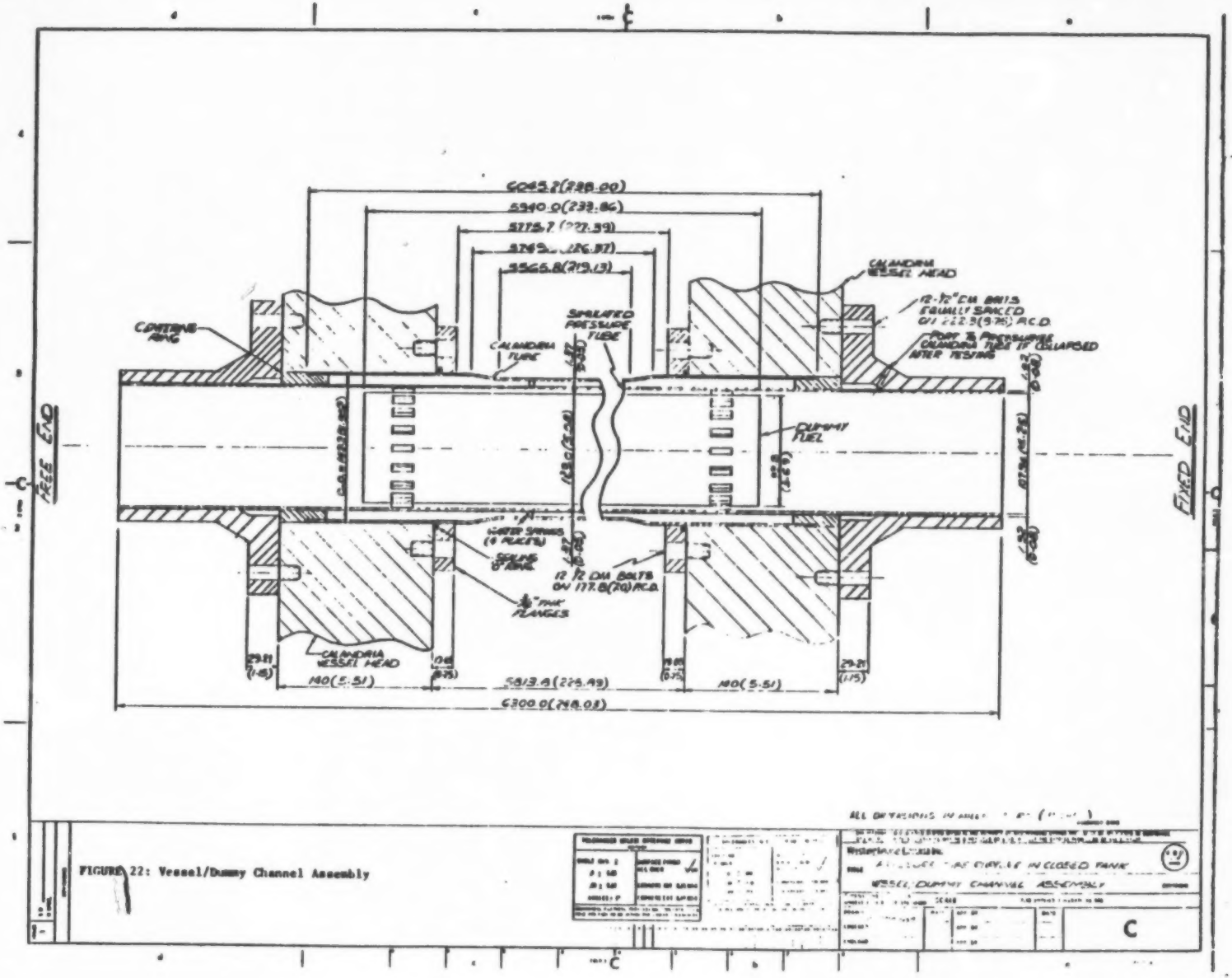


FIGURE 21: Vessel/Target Channel Assembly


6045.2(238.00)
5940.0(233.86)
5775.7(227.39)
5765.8(219.13)
CALANDRIA VESSEL HEAD
12-1½" DIA BOLTS EQUALLY SPACED ON 222.3(9.75) P.C.D.
CONTAINS RING
SPIRALLED PRESSURE TUBE
CALANDRIA TUBE
FREE END
FIXED END
FUEL
WATER SPRINGS (4 PLACES)
SPLINE & KEY
12-1½ DIA BOLTS ON 177.8(7.0) P.C.D.
¾" THK FLANGES
CALANDRIA VESSEL HEAD
140(5.51)
5813.8(228.89)
140(5.51)
6300.0(248.03)
FIGURE 22: Vessel/Dummy Channel Assembly
VESSEL/DUMMY CHANNEL ASSEMBLY
C

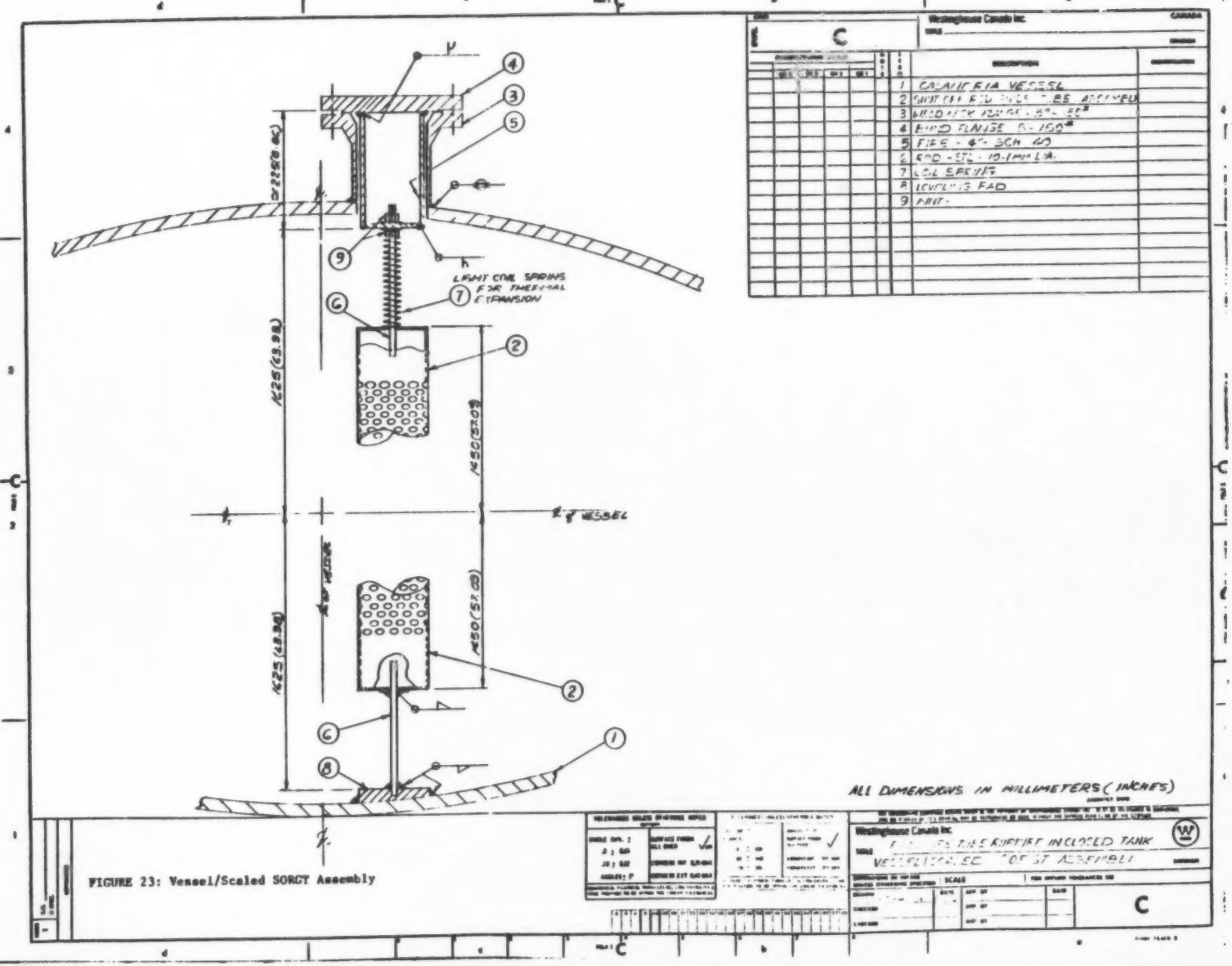


FIGURE 23: Vessel/Scaled SORGT Assembly

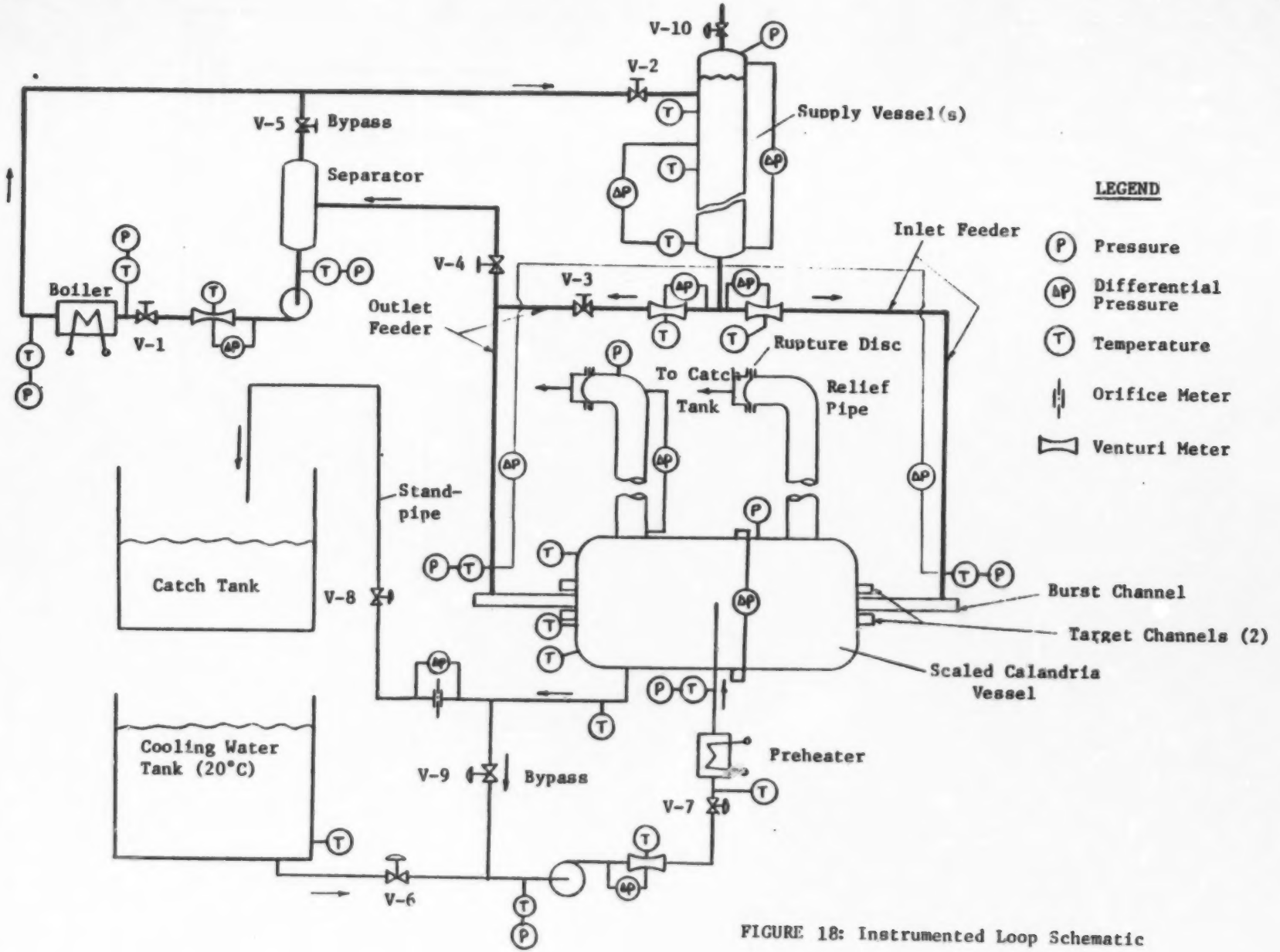


FIGURE 18: Instrumented Loop Schematic

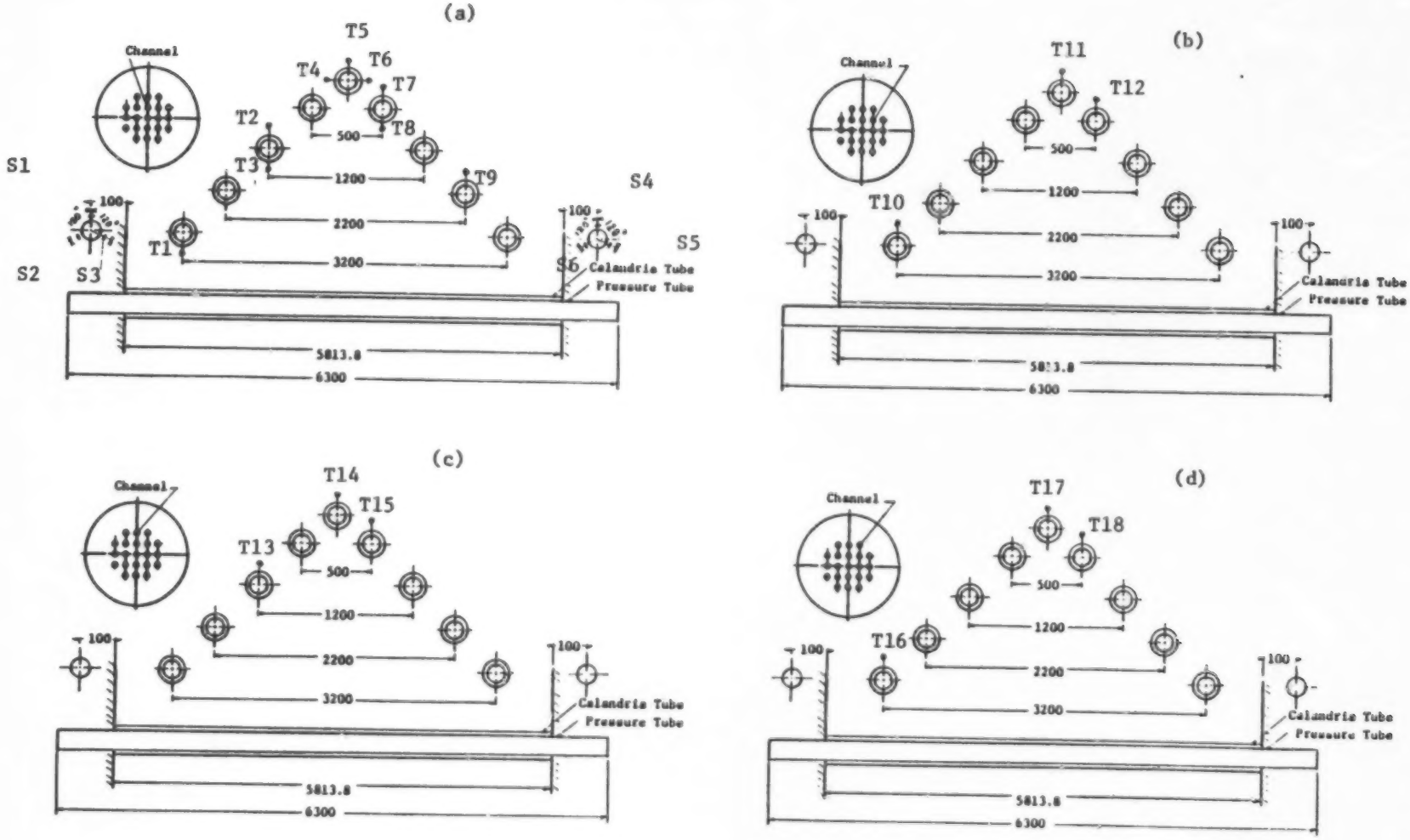


FIGURE 24: Thermocouple (T) and Strain Gauge (S) Distribution

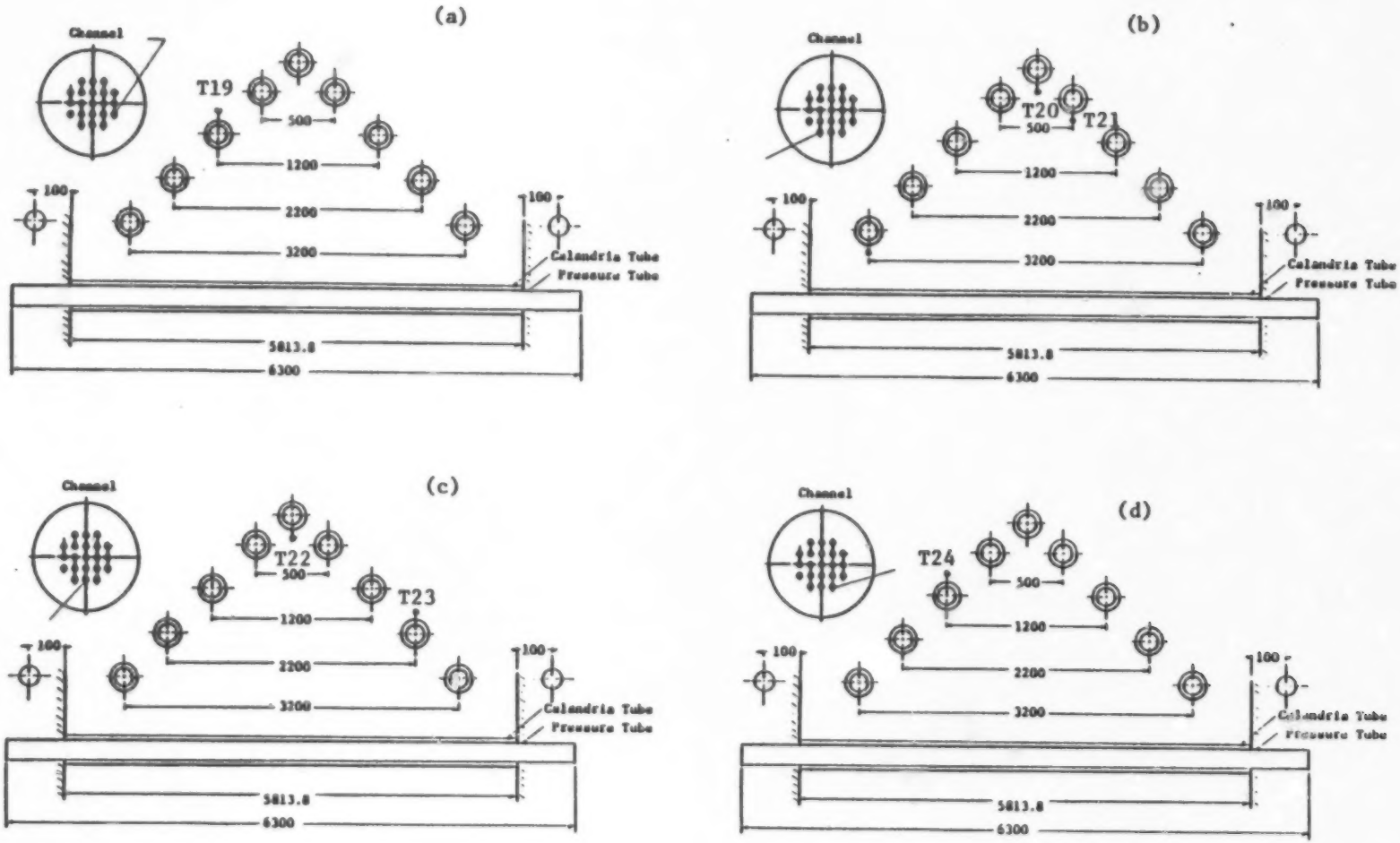


FIGURE 25: Thermocouple (T) and Strain Gauge (S) Distribution

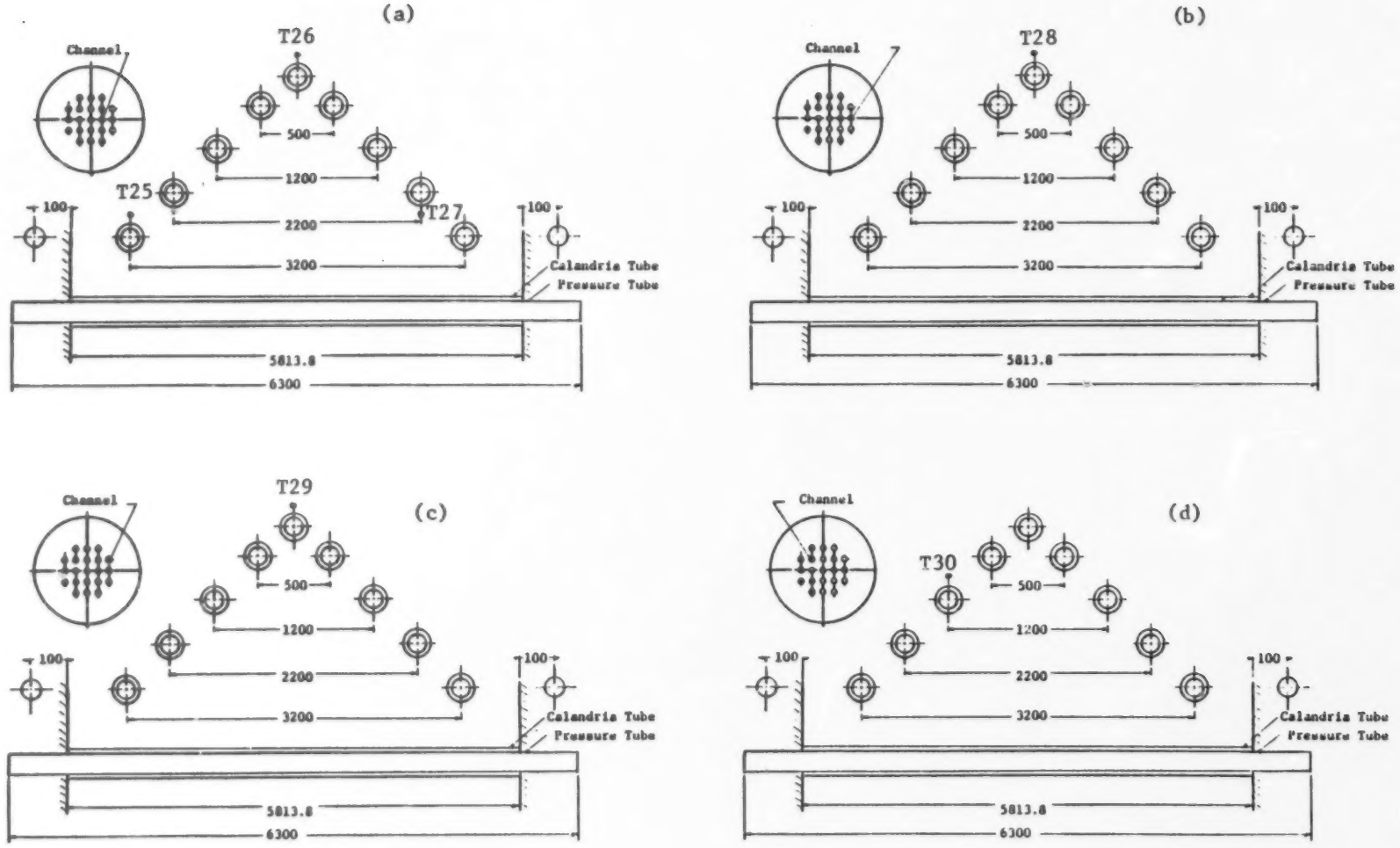


FIGURE 26: Thermocouple (T) and Strain Gauge (S) Distribution

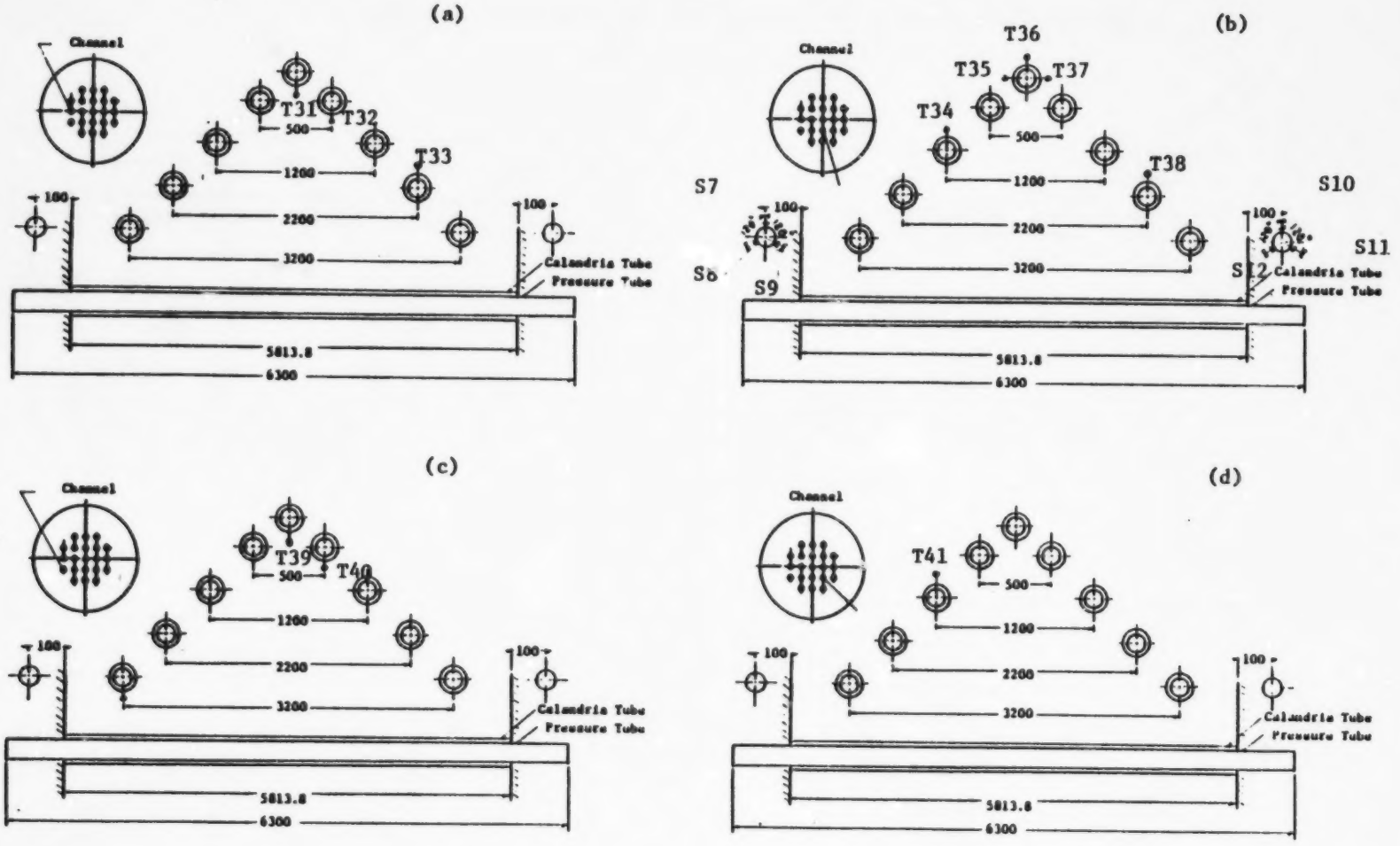


FIGURE 27: Thermocouple (T) and Strain Gauge (S) Distribution

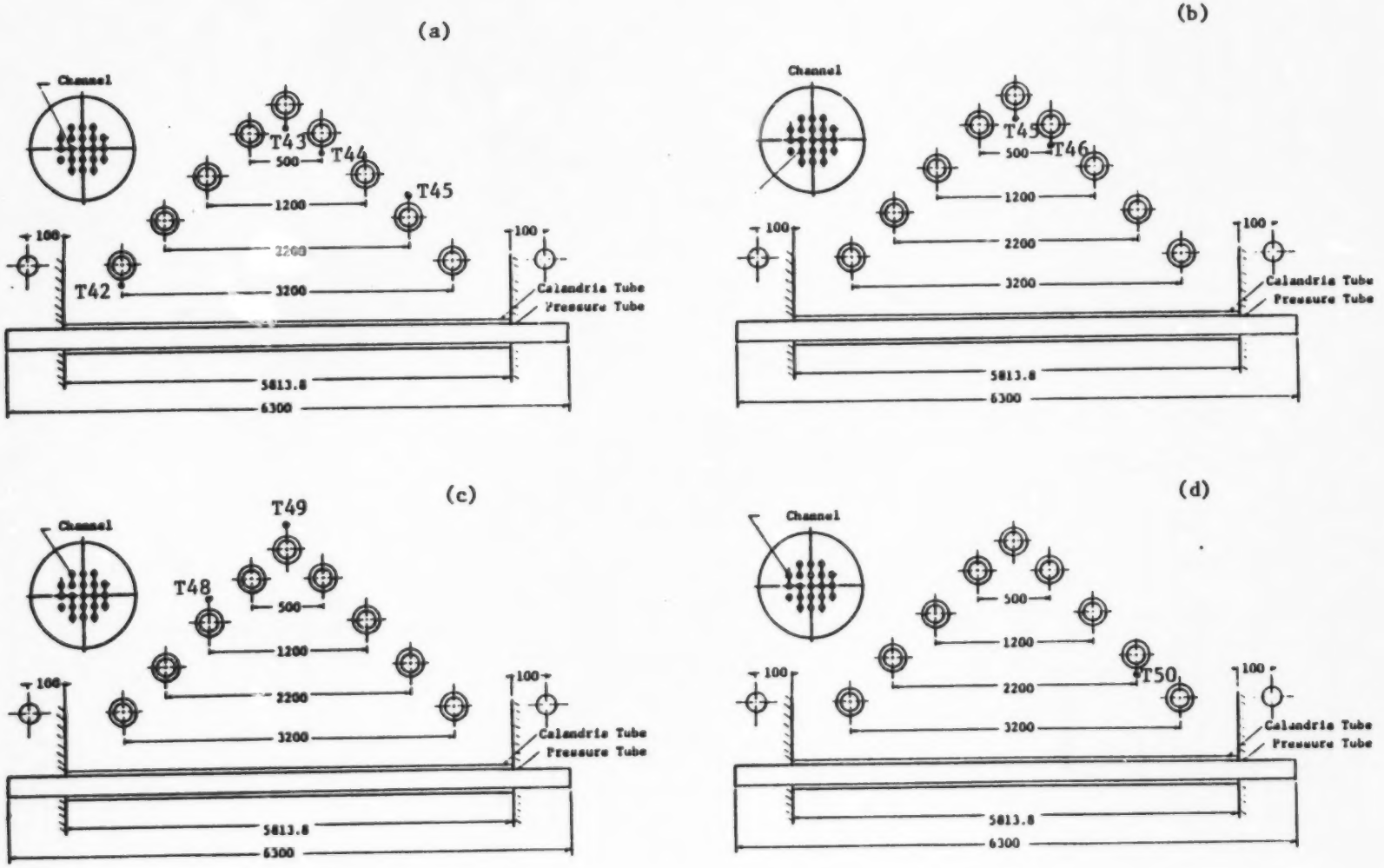


FIGURE 28: Thermocouple (T) and Strain Gauge (S) Distribution

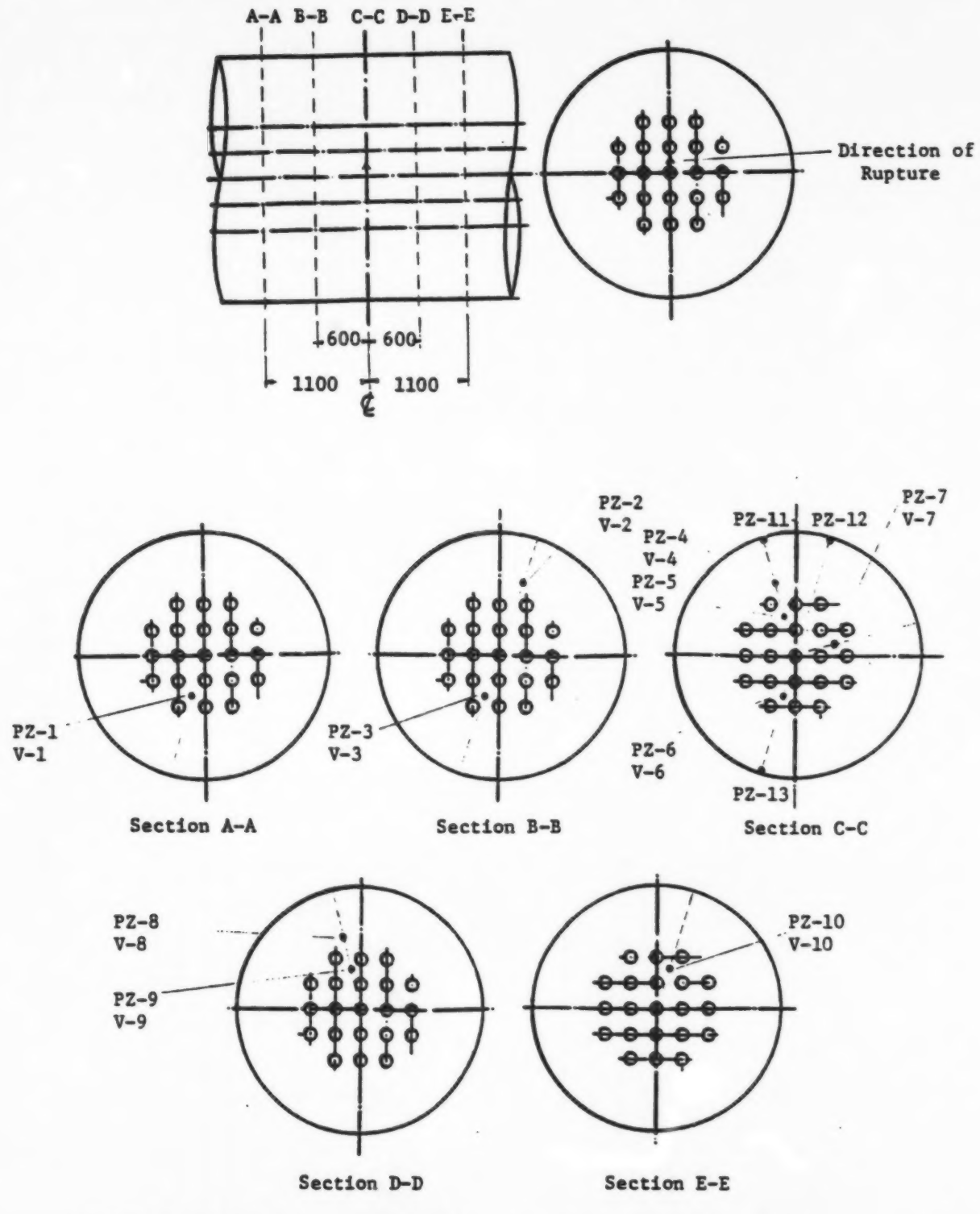


FIGURE 29: Distribution of Dynamic Pressure Transducers (PZ) and Void Probes (V) (void probes are placed near all the interior dynamic pressure transducers)

APPENDIX A

'STATEMENT OF WORK'

DSS RFP 50SS.87055-4-4029, JUNE 28, 1984

ANNEX "A"

STATEMENT OF WORK

Project Title: Pressure Tube Rupture in a Closed Tank
Phase I: Feasibility Study

1.0 Background Information: A technology review on consequences of pressure tube rupture on in-core components has been conducted for the Atomic Energy Control Board (AECB) by the University of British Colombia (UBC). One of the recommendations of the UBC report is that a closed, scaled-down (in diameter only, length will be full size) cylindrical vessel (model of a CANDU-600 calandria vessel) within which pressure tube rupture tests at full scale system conditions can be conducted is required to determine the resulting loadings and extent of damage to different in-core structures.

2.0 Objective: The primary objective of the overall project is to investigate: i) the thermohydraulic phenomena associated with a postulated pressure tube/calandria tube (PT/CT) rupture at normal and abnormal (events causing over pressure incidents) reactor conditions, and ii) the resulting loadings on shut-off-rod guide tubes and other PT/CT assemblies (all of the PT's and CT's will be full scale). The phenomena expected to take place include i) shock waves, ii) transient bulk pressurization, iii) jet discharge (flashing, periodical bubble expansion and collapse), and iv) other possible damaging mechanisms that may be identified (e.g. vibration, etc.). Provision is required to record with a high speed camera the resulting thermohydraulic behaviour and the structural deformation/displacement/ disassembly of the simulated in-core structure.

The end product of this feasibility study shall include: i) a set of specifications for the test assembly, ii) general arrangement drawings, iii) a proposal for a test matrix, iv) a survey of existing facilities which could provide the required high pressure, temperature and fluid inventory, and recommendation of the most appropriate facility, and v) a cost estimate for the detailed design and construction, instrumentation, conducting the test program and reporting. The estimate should also include the cost of potential modifications, to the recommended facility, which may prove necessary to accommodate the test assembly.

3.0 Range, extent and bounds of the work (scope): This feasibility study would include: i) recommendation of a calandria vessel scaling scheme and special design features which would not hinder representative thermohydraulic phenomena and structural response to occur, ii) defining a procedure to initiate the tube rupture, in consultation with AECB staff, iii) defining the required instrumentation coverage to fully characterize the thermohydraulic phenomena and the structural response, iv) proposing a test matrix in consultation with AECB staff with a progressive test plan which would avoid damaging the tube array prematurely, v) selection of an appropriate test facility, and vi) providing a detailed cost estimate as discussed in 4.5 below. The test facility must include:

3.1 An array of at least nine (3x3) Zr-Nb pressure tubes and PT/CT assemblies (one rupture pressure tube and eight surrounding PT/CT assemblies). A provision to increase the array to 5x5 with the addition of mild steel pressure tubes and Zr-2 calandria tubes

should be taken into account. Provisions for including representative weights into target assemblies (immediately adjacent to the rupture tube) and dummy fuel bundles in the rupture tube itself should be considered.

3.2 Vertical shut-off-rod guide tubes at different axial locations (at least two rows at different radial locations on the same side of the break).

3.3 Ordinary water should be used for both the hot, discharging fluid and the surrounding cold fluid in the vessel to realistically generate the expected bubble expansion and collapse phenomenon.

3.4 Sufficient hot water inventory for discharge through the rupture for at least two minutes to enable characterizing delayed thermohydraulic phenomena and structural response.

3.5 Fast response pressure transducers to track the pressure wave propagation and attenuation.

3.6 Provision for recording the post rupture behaviour with a high speed camera through special windows in the vessel wall.

4.0 Tasks to be Performed:

4.1 Comprehend, as a background information, the UBC state-of-the-art technology review (issued as AECB Report # INFO-0115, 132 pages).

4.2 Recommend a calandria vessel scale ratio, design features and fluid conditions that would allow: i) generation of all representative pressure transients, ii) characterization in full detail of the thermohydraulic phenomena and associated structural loadings, and iii) inspection of the tube array and shut-off-rod guide tubes following each test.

4.3 Propose a procedure to initiate the pressure tube rupture, in consultation with AECB staff.

4.4 Recommend instrumentation coverage and methods of data acquisition and reduction.

4.5 Propose a test matrix in consultation with AECB staff.

4.6 Survey the existing facilities which could provide the required test conditions, and recommend the most appropriate facility.

4.7 Once the test facility/assembly characteristics are identified, ensure that the break discharge rate anticipated following a pressure tube rupture is comparable to that of a corresponding CANDU-600 case.

4.8 Prepare a detailed cost estimate for: i) the design and construction, instrumentation, conducting the test program and reporting, and ii) potential modifications which may prove necessary to accommodate the test assembly in the recommended test facility.

4.9 Discuss in detail with AECB staff and then finalize the set of specifications and the choice of instrumentation. Produce general arrangement drawings.

4.10 Document items 4.1 to 4.9 above in a report.

5) Deliverables:

a) Progress or milestone reports

i) frequency: Every month
ii) no. of copies: 4 (Four)
iii) contents instructions: The report shall detail the progress to date, the status of work, and indicate whether the work is on schedule and any anticipated problems.

b) Interim Reports

i) frequency: One, after the completion of Tasks 4.1 to 4.5.
ii) no. of copies: 5 (Five)
iii) contents instructions: Each report shall detail the work completed in each Task including figures and tables.

c) Draft final report(s): (note: iterations of the draft final report will be submitted as required)

i) delivery date: Not later than 31 January 1985
ii) no. of copies: 5 (Five)
iii) bilingual requirements: none
iv) format instructions: An AECB style manual (to be supplied by AECB to the contractor) will guide in the preparation of the final report.
v) contents instructions: The report shall detail the work performed, and shall include figures and tables and a list of contents which will appear in the final report. Within 3 weeks, at a mutually agreed time, a debriefing seminar will be given at the AECB Ottawa office on the contents of the final draft report.
vi) The contractor shall, iteratively, take account of AECB staff comments.

d) Final report:

i) delivery date: Not later than 29 March 1985
ii) no. of copies: Original + 5 copies
iii) bilingual requirements:
iv) format instructions: The report must contain an abstract in English and French and a disclaimer (to be supplied by AECB) in English and French. In addition, the report must bear AECB research report covers and an AECB title page (all to be supplied by AECB).
v) contents instructions: The report shall include an executive summary of the findings and enumerated recommendations.

e) Progress Meetings:

i) number: 4 (Four)
ii) dates: After completion of Tasks 4.1 to 4.3, after completion of Tasks 4.4 and 4.5, at the onset of Task 4.8 and after completing Task 4.10.
iii) additional requirements: An interim report must be presented at the second progress meeting. The draft final report must be presented at the fourth progress meeting.

f) Briefing and debriefing Meetings:

i) number: 2 (Two)
ii) dates: At the onset of work and not later than 22 February 1985
iii) additional requirements: At the first meeting, the contractor will present the plan for conducting the project. At the second meeting, the contractor shall give a seminar on the contents of the final report to AECB staff at the AECB Ottawa Office.